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THESIS

TELEMETRY SYSTEMS ANALYSIS AND DESIGN

by

William K. Ham

December 2000

Thesis Advisor: Brij Agrawal

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The Navy has a valuable opportunity to improve its own products and operations efficiency by showing its future leaders and designers how to design effective and viable telemetry, tracking, and commanding (TT&C) systems, and their operation. One system is the FLTSAT military communications constellation of spacecraft, one of which has been a static display at the Naval Postgraduate School (NPS) until June, 2000. The primary objective was to make this spacecraft operational and thus provide a new operational spacecraft laboratory for other NPS students. This thesis may also be used as a primer for the space engineering or space operations student regarding TT&C systems design. Great effort has been taken to document and discuss current design practices and standards adopted by DOD laboratories, test facilities, and operations centers. A TT&C system designed for a spacecraft incorporating all the traditional subsystems (payload, thermal, structural, power, TT&C, attitude control) is included.

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TELEMETRY SYSTEMS ANALYSIS AND DESIGN

William K. Ham
Lieutenant, United States Navy
B.S., Texas Tech University, 1993

Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

The Navy has a valuable opportunity to improve its own products and operations efficiency by showing its future leaders and designers how to design effective and viabletelemetry, tracking, and commanding (TT&C) systems, and their operation. One system is the FLTSAT military communications constellation of spacecraft, one of which has been a static display at the Naval Postgraduate School (NPS) until June, 2000. The primary objective was to make this spacecraft operational and thus provide a new operational spacecraft laboratory for other NPS students. This thesis may also be used as a primer for the space engineering or space operations student regarding TT&C systems design. Great effort has been taken to document and discuss current design practices and standards adopted by DOD laboratories, test facilities, and operations centers. A TT&C system designed for a spacecraft incorporating all the traditional subsystems (payload, thermal, structural, power, TT&C, attitude control) is included.

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I. INTRODUCTION

A. PURPOSE

This thesis may be used as a primer for the space engineering or space operations student regarding TT&C systems design. Great effort has been taken to document and discuss current design practices and standards adopted by DOD laboratories, test facilities, and operations centers. A TT&C system designed for a spacecraft incorporating all the traditional subsystems (payload, thermal, structural, power, TT&C, attitude control) is included.

B. RESEARCH OBJECTIVES

1. Primary Objectives

a. Apply current principles and design techniques to develop a Telemetry, Tracking and Commanding (TT&C) system for a small spacecraft incorporating as many traditional subsystems as possible (payload, thermal, structural, power, TT&C, attitude control).

b. Recommend appropriate hardware and software compliant with current DOD telemetry standards.

c. Document current practices and principles for designing spacecraft telemetry systems in a reference tool for use by other space systems students.

d. Demonstrate integration of TT&C control software with the FLTSATCOM spacecraft in the Space Systems FLTSATCOM Laboratory, contingent upon successful power up of the spacecraft. This would result in active communications with the spacecraft and possible future use as a hands-on student laboratory.

2. Secondary Objectives

a. Explore various compression techniques to improve telemetry data rates.

b. Explore innovative designs used in experimental spacecraft.

c. Investigate design limiting issues from both the engineering perspective and the operator perspective.

C. THESIS OUTLINE

I. INTRODUCTION

II. BACKGROUND

III. DATA ACQUISITION

A. Optical Transducers

B. Strain Transducers

C. Thermal Transducers

D. Position Transducers

E. Data Acquisition Systems

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V. TELEMETRY FRAME CONSTRUCTS AND STANDARDS

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VI. COMMANDING

A. Fundamentals of Commanding

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C. Hardware Configuration at NPS

D. Software Configuration at NPS

E. Commanding Operations at NPS

VII. TT&C SYSTEM FOR A SPACECRAFT

A. Introduction

B. Requirements

C. Trade Studies

D. Final Design

D. EXPECTED BENEFITS OF THIS THESIS

There are several applications for this product. Any engineering team involved in a satellite design project, may find it a suitable baseline for the TT&C subsystem. The content could be formulated into course notes for implementing a course on TT&C system design, currently no course is offerred at the Naval Postgraduate School on this subject. Additionally, the successful implementation of active communications with the currently inoperable FLTSATCOM spacecraft in the Aerospace Engineering Building, has far reaching implications. Such a project not only provides opportunity to demonstrate the importance of operator interface to engineers, which is often forgotten in the design process, but also provides a platform for future students to conduct research or laboratory work. It is also possible that a future course may develop from this work, which may become at least an optional elective for future students of engineering systems design.

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II. BACKGROUND

A. INTRODUCTION TO TELEMETRY, TRACKING AND COMMANDING SYSTEMS

Spacecraft design incorporates many different disciplines. All of which contribute to the success of the mission for which the spacecraft is designed. All are equally important, in that if one was less important it would have been removed from the design process ages ago since every subsystem has mass, and mass is the main expense. One subsystem, however, has special consideration. Without it, other subsystems could not operate to carry out the mission. Additionally, it is the only link the operator or designer has to the spacecraft once it is on orbit. The Telemetry, Tracking and Commanding (TT&C) system is the central nervous system of any spacecraft, and also serves as the primary input and output for all the other subsystems. An introduction to the main functions of the TT&C system is in order: communications, data acquisition, system operations (commanding), and data/command storage.

Communications is the best place to start. After all, it is the only means by which we can do anything to the spacecraft once on orbit. Through highly reliable communications equipment and techniques, ground resources may communicate with the spacecraft whenever allowable. Why not at any time? Simply stated, an operator may not be able to see the spacecraft at any time. Ground resources are limited by dollars. That is, it may not be economically feasible to construct enough ground stations to ensure visibility to the spacecraft all the time. This is especially true for low altitude satellites. Additionally, the spacecraft may be in an attitude that is not optimal. A tumbling spacecraft requires communication with the ground to be recovered, therefore, communications must be possible from any orientation. This is usually acieved by strategic placement of antennas in the nadir and anti-nadir directions of the spacecraft. Such antennas are usually low power to achieve the requisite four pi steradian coverage, or communication from any direction. Thus the communications subsystem must be very reliable to ensure every opportunity to talk to the spacecraft is effective, which may only be a span of five minutes. Similarly, the reverse is true. For the operator or engineer, it is just as important for them to hear what the spacecraft has to say. After all, a reaction to a situation can only be initiated after knowledge of the situation has occurred. Thus the

means by which the spacecraft understands what is happening to it while on orbit is important as well. This mechanism is the onboard processor and any peripheral components utilized to make these assessments. The processor is the director of all other subsystems to ensure the mission is successful. Certainly the operator or engineer tells the processor what to do, but really the processor is the one that carries out the orders while on orbit. It is clear that computer communications is essential to successful system design.

The interdisciplinary nature of TT&C systems contributes to the complexity of the design problem. Since most engineers tend to focus on one area (attitude control, guidance, structures, thermal, etc.), few can effectively describe interaction among them all. Previously the interactive nature of the TT&C system was outlined. It communicates with everything: other subsystems, itself, and the operator. This is depicted in Figure 1. An analogy is in order: for a person to be able to speak about several different topics, or even to be able to speak to several different types of professionals (doctors, lawyers, engineers, school teachers) they must have a rudimentary knowledge of that which they speak. This is not unlike the TT&C system designer and by extension, the system to be designed. To understand thermal data, the system must understand the difference between values that are acceptable and unacceptable. The same is applied to attitude control data. An understanding of something implies a knowledge base from which to draw from. For a TT&C system, this knowledge base is the software. It provides the thinking capacity for the spacecraft. It can facilitate comparison of actual values with a database of known acceptable values. And when a problem arises, the software can tell the processor to execute a series of safing commands which will configure the spacecraft in a known state until help arrives in the form of commands from the ground. To understand the data, however, data must exist in the first place. This brings to light the means for collecting data: the data acquisition system. This is probably the most overlooked component of the TT&C system. Most design texts speak of the sensors or transducers, which measure the stimulus, and the transponders, which transmit the data to the ground. The step in between is just as critical. This is the feet, if you will, that get the information from sensed value to communicated values. Not only is it important to understand this process, but it is critical to properly determining the TT&C system resource requirements (processor speed, data storage capacity, downlink bandwidth).

The thinking mechanism, the software, was only briefly mentioned, and requires greater attention. This is the means by which the processor decides to do something or to not do something. Operating the spacecraft requires being able to conduct several

functions successfully while it is out of view of the operator. Some of these functions include maintaining proper attitude, ensuring adequate power profile, calculating ephemeris data, storing telemetry data, and maintaining the proper thermal environment

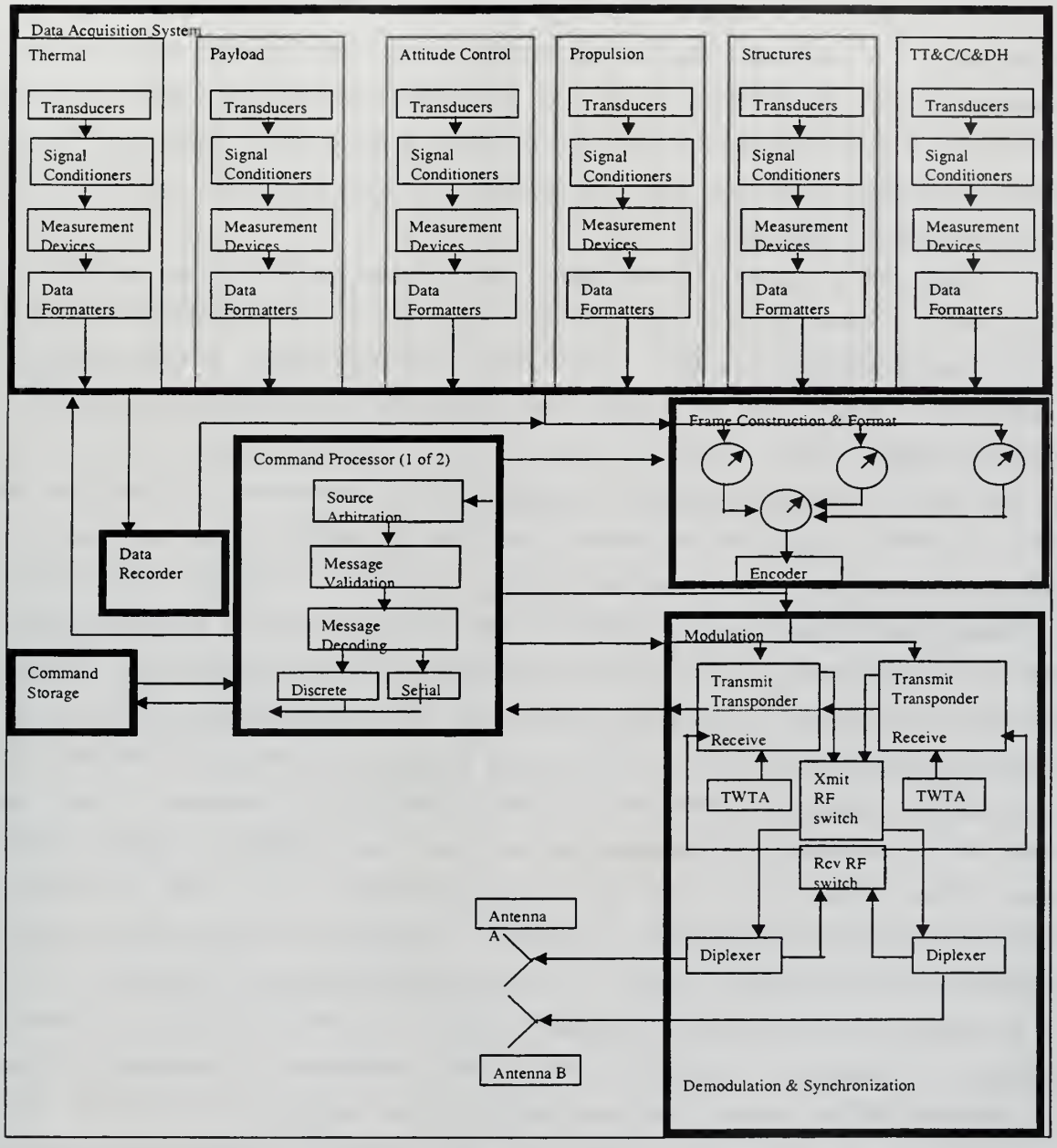

Figure 1. Overview of a TT&C System

[Ref. 1]. All these require decisions which must be made via software. Software is an interesting problem in itself. It has become a primary driver in system development costs, and is considered by many to be a subsystem all its own [Ref. 1]. Because software is so nebulous, large margins are used in estimating the costs and size [Ref. 1]. Software is one of the few things that can actually be changed after launch. This said, a limited scope will be explored. Key concerns include understanding what functions must be performed, and estimating the amount of memory to store all the software required for system operation. The former so proper size of the processor in terms of speed can be assessed. Thus all required instruction executions can be completed. The latter so enough memory can be planned for onboard the spacecraft.

Recall that a spacecraft is not able to communicate with the ground operator 24 hours per day. Ground stations, are the primary reason for this constraint [Ref. 1]. This is a critical and fundamental concept to understand in the system design. An old adage lends a great deal of insight here: 'If a tree falls in the forest, and no one is there to hear it, does it make a sound?' When a spacecraft is out of view, it does still operate. Temperatures still rise and fall, voltages continue to supply power to components, and problems do occur. So what action does the operator take when the satellite comes into view, and finds the spacecraft in a non-nominal health status? Typically it is desirable to know when the change occurred, since it is not likely that the spacecraft was left in this configuration when it was last viewed. So the system must be able to play back some portion of health data since the last time the spacecraft was in view. Play data back requires that it must have been stored in the first place. Thus a data storage unit is required to facilitate this main function. Along the same line of thinking, invariably it is necessary to have the spacecraft do something like perform a payload operation, or perform something health related when it cannot be viewed from a ground station. To do this, the onboard processor is the agent that will carry out the task. Carrying out the task requires that the processor look for the specific action or file at a predetermined time for execution. Thus the processor must have some storage buffer where it can find these actions, command storage. It is important to realize that with at least a rudimentary understanding of how the spacecraft will be operated, adequate flexibility can be designed into the system. This understanding can be obtained by observing missions which are similar and have already been deployed, or by specifying certain absolute requirements from an operational point of view. Both are techniques used in practice. When considering the significance of the TT&C system, and its relevance to mission success, its critical nature to the spacecraft

design is plain to see. It is with this mindset that the resulting research into TT&C systems and how to design them is now presented.

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III. DATA ACQUISITION

One of the primary objectives of any TT&C system is to collect output data from spacecraft components [Ref. 5]. Collection of the data requires that we know what is being collected and how it is measured. The transducer converts one form of energy, temperture, force, or pressure into another, typically electrical voltage because it is easily measured. Generally, we want the transducer to measure some phenomena which may be occurring on our spacecraft: temperature of a component, presence of the sun in a sensor, whether a thruster is on, etc. Transducers are the means by which we collect the data we desire. Several transducer types are avaliable to the design engineer, and a few of those most often will be introduced.

A. OPTICAL TRANSDUCERS

An optical transducer converts luminous information or phenomena into a measureable electrical voltage or current [Ref. 2]. These transducers typically respond to a broad range of spectral frequencies. Therefore, to gain adequate spectral resolution, spectral filters are employed. A few applications of these devices include: sun sensors, earth sensors, electronic cameras [Ref. 1]. The physical phenomena that make these devices work is the photoelectric effect. There are two classes of optical devices: point photoelectric devices and area photoelectric devices. Point devices consist of photomultiplier tubes, phototransistors, photodiodes, and photocells. The mose complex of these is the photomultiplier tube. Area photoelectric devices are often called Charge Coupled Devices (CCD) [Ref. 2].

1. Photomultiplier Tube

These devices are used to measure very faint levels of light through a very limited aperture. The sensitivity provides for measurements of as little as a few photons per second. This device does not work well when saturated with a bright source. Because very faint levels of light are difficult to measure accurately, the device is constructed of multiple stages of photoelectric material resulting in a cascade of electrons at the final stage which is measureable as current. The stages of photoelectric material, called dynodes, are the key to the operation of this device. Electrons are acclerated through

each stage where a collision with other photoelectric material occurs at the end of the stage. Thus more electrons leave the stage than entered the stage. As many as ten dynodes are used in the typical photomultiplier tube. High voltage power supplies are required to drive the tubes to ensure a potential difference across all the stages of approximately 1000V. [Ref. 2]

Photomultiplier tubes are characterized by three things: quantum efficiency, dark current, and fatigue properties. Quantum efficiency refers to the number of photons actually detected by the device [Ref. 2]. Response curves displaying quantum efficiency versus wavelength are generally obtained through the manufacturer and are non-linear. Such curves typically display a disproportionate response at particular wavelengths, thus the tube is chosen based on its response curve at the wavelength of interest. Dark current is a description of the tube's intrinsic noise level when not illuminated [Ref. 2]. This current is largely due to thermal excitation, and can be reduced to some degree by active thermal control. Fatigue is a property in all tubes which results in a change in output current while under a consistently bright load. It often manifests as a 'drift' in output current over time. Closing the aperture for a short duration, or cycling the aperture often will help to prevent fatigue in most cases. This property and dark current are especially damaging during extended calibration periods where precise measurements are required [Ref. 2].

2. Phototransistors, Photodiodes, and Photocells

Unlike the photomultiplier tube, these devices are used to measure incident light when the source is much more bright, such as a heavenly body that is relatively close to the detector eg. Sun or Earth for a Low Earth Orbiting (LEO) spacecraft. The measurement is produced in a discrete fashion. The response curve for these devices is generally logarithmic over several decades of illumination, thus giving them a linear plot on a log-log graph. The output current is generated in the transistor or diode when the light is present. These semiconductor devices change electrical states at the P-N junction in the presence of light [Ref. 2]. Photocells, on the other hand, change the cell material's resistance when light is present.

3. Charge Coupled Devices

CCDs are configured in arrays of photosensitve detectors. Both linear arrays and two dimensional arrays are often used. Each detector is essentially a storage device which stores charge based on the incident number of electrons over a sample duration [Ref. 2]. Once the duration is complete, the charge is released to a buffer. This transfer of charge can be measured as a voltage which is proportional to the intensity of the incident light. For an array, each detector voltage is sampled in sequence not unlike retreiving data from a memory array. Applications for the CCD array are found in imaging payloads as well as high speed tracking systems [Ref. 2].

B. STRAIN TRANSDUCERS

Whenever a force or pressure measurement is desired, typically the best way to obtain this is observing the material which is undergoing stress due to the force or pressure. Materials will undergo a certain amount of elastic deformation when a force is applied to them. This strain can be measured via a transducer that is attached to the material itself. Two types of transducers are generally used for this measurement: strain gauge and piezoelectric crystal.

1. Strain Gauge

Strain gauges have been widely used in engineering projects for generations. These are simple devices that exploit a material's well known resistivity property. Physical construction of a strain gauge, or strain rosette, consists of a wire or metal foil attached to a thin paper or plastic backing which facilitates bonding directly to the surface whose strain is to be measured [Ref. 3]. When the material stretches along the axis of the grid, the length of the wire changes, and thus a change in the resistivity occurs. Recall that resistance is given by the following equation:

$$R = \frac{\rho \cdot L}{A} \qquad \text{Equation 1}$$

where ρ is the intrinsic resistivity of the wire, L is the length of the wire, and A is the cross-sectional area of the wire.

Unfortunately, if the wire stretches along the perpendicular to the grid axis, no change in resistivity occurs. So to make measurements in this direction, the gauge would need a second foil, whose axis is perpendicular to the first. This is not widely used in practice. Industry typically uses the 45° rectangular rosette consisting of three foils, the center foil sandwiched between two side foils at 45°, or the 60° equiangular rosette also consisting of three foils separated by 60°. Figure 2. depicts these rosettes. From these configurations, not only can extensional strain be measured as in a single gauge, but shear strain can also be measured, often referred to as multi-gauge. [Ref. 3]

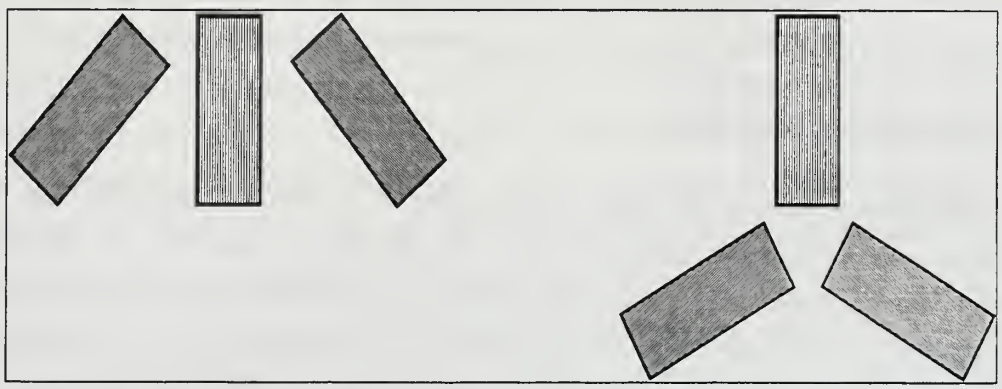

Figure 2. 45° Rectangular Rosette and 60° Equiangular Rosette After Ref. [3]

2. Piezoelectric Gauges

Piezoelectric materials react to transient changes in the crystalline structure of the material. When a crystal is compressed, a voltage is produced across the material. This voltage will dissipate if the acting force remains constant. Thus instantaneous measurements are only possible for actively moving materials. Vibrational displacements are the primary measurements these gauges are used for. The output for these gauges is linear over a large temperature range, making them attractive for space applications. Also, the crystals output fairly large voltages, on the order of milivolts, which enables them to be utilized without too much signal conditioning.

C. THERMAL TRANSDUCERS

A second class of devices that exploit the resistivity property of a material are the thermal transducers. Here the principal that the resistance of the device changes with temperature is at play. Three types of transducers are in widespread use: resistance temperature detectors (RTDs), thermocouples, and thermistors. Of the three, the RTD is the most linear.

1. Resistance Temperature Detectors

The most common material used in RTDs is platinum. In general the temperature-voltage relationship is given by an equation of the following form:

$$R_T = R_0 \cdot (1 + \alpha \cdot T) \qquad \text{Equation 2}$$

where R_T is the resistance at temperature T, R_0 is the calibrated resistance, and α is the coefficient of resistance change in units of $\Omega/\Omega/°C$ where Ω is the unit of resistance in ohms. This is a general relationship, and the coefficients change depending on the material used. A more exact relationship with platinum, and that is found in most modern labs, utilizes a 20^{th} order polynomial [Ref. 2]. Actual implementation of the RTD employs the two or three wire Wheatstone bridge as depicted in Figure 3.

2. Thermocouples

This commonly used device is based on the principal described by the Seebeck effect: every junction of two dissimilar metals will produce a potential difference across the junction [Ref. 2]. This voltage is not constant, but is a function of the material types and temperature. Advantages for using thermocouples include: greater resistance to damage, ease of manufacture and placement, larger operating range. The Seebeck effect not only provides the means for temperature measurement, it also provides the single most significant disadvantage [Ref. 2]. Because every dissimilar metal produces a potential difference, probes, inputs, and sockets contribute to this voltage. Separating these contributors from the voltage of interest requires a great deal of added design complexity. Additional powered equipment to maintain isothermal blocks for the two metals are generally required, which contributes to the complexity of the system design.

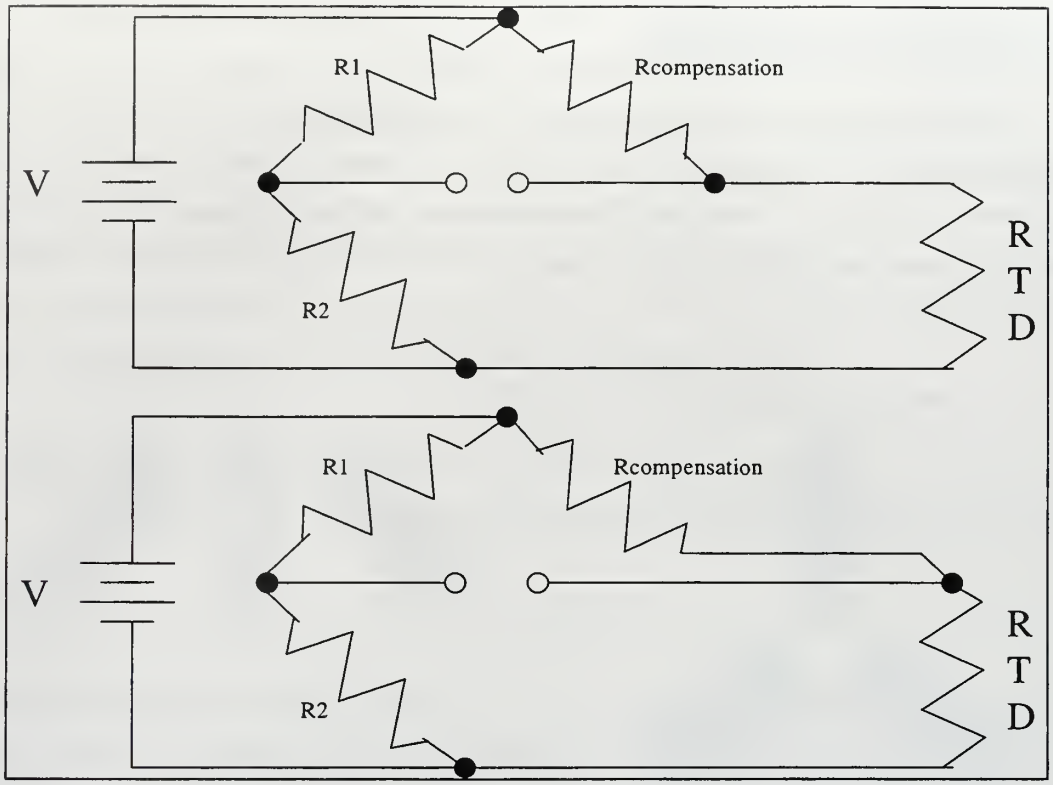

Figure 3. Common RTD Measurement Configurations After Ref. [2]

Another disadvantage is the nonlinearity of the operating characteristics. Successfully implementing these devices requires proper signal conditioning, careful placement of measurement leads, and for adequate resolution, reliably reading measurements on the order of microvolts.

3. Thermisters

This is a semiconductor device that must be maintained below the maximum operating temperature and not subject to much mechanical stress [Ref. 2]. It has a very steep negative slope coefficient, which allows much more resolution in small temperature changes. The following equation can be used to obtain resolution on the order of 0.04°C over a 100°C temperature range:

$$\frac{1}{T} = A + B \cdot \ln(R) + C \cdot [\ln(R)]^3 \qquad \text{Equation 3}$$

where A, B, and C are constants specific to the device, and T is temperature in K [Ref. 2]. This device is also implemented in a Wheatstone bridge circuit as in the RTD.

D. POSITION TRANSDUCERS

While moving parts are typically undesirable in a spacecraft design, it is sometimes unavoidable. Accurate position is very important on a spacecraft when implemented. For example, the solar wings are pointed to the sun to ensure power to the spacecraft payload and bus. Some type of motor is necessary to rotate the wing shaft to maintain sun pointing. Knowledge of this position accurately can mean the difference between the batteries being in a charging state or discharging state. For a LEO spacecraft, an error can lead to drastic results, as the batteries are charged and discharged every orbit. With this significance in mind, there are two basic types of position sensors: resistive measurements and optical sensors.

1. Resistive Distance Measurements

The most inexpensive device is, in general, not the most accurate either. The same truism applies to resistive distance measurements. These devices are potentiometers that are mechanically coupled to the displacement of interest [Ref. 2]. As the displacement increases, so does the resistance in the potentiometer. Voltage drop across the potentiometer is proportional to the displacement at any time. As observed in the temperature measurement devices, resistance is subject to change with temperature. The solar wing drive motors we discussed previously are also typically at a location that is in direct line of sight of the sun, which heats the potentiometers while in view. Thus the resistance changes depending on whether the spacecraft is in sunlight or in eclipse. Resistance dependence on temperature is one of the disadvantages of these devices, as well as the nonlinearities associated with the drive motor [Ref. 2].

2. Optical Distance Measurements

An optical sensor is usually used to get very precise measurement results. Often these sensors are used to measure rotary displacement and may be found in applications such as antenna pointing or telescope positioning. A binary encoded disk is placed

concentric to the rotating shaft (see Figure 4.). When the shaft turns, the disk does also, changing the code. A string or bank of photodiodes and photo detectors are placed just

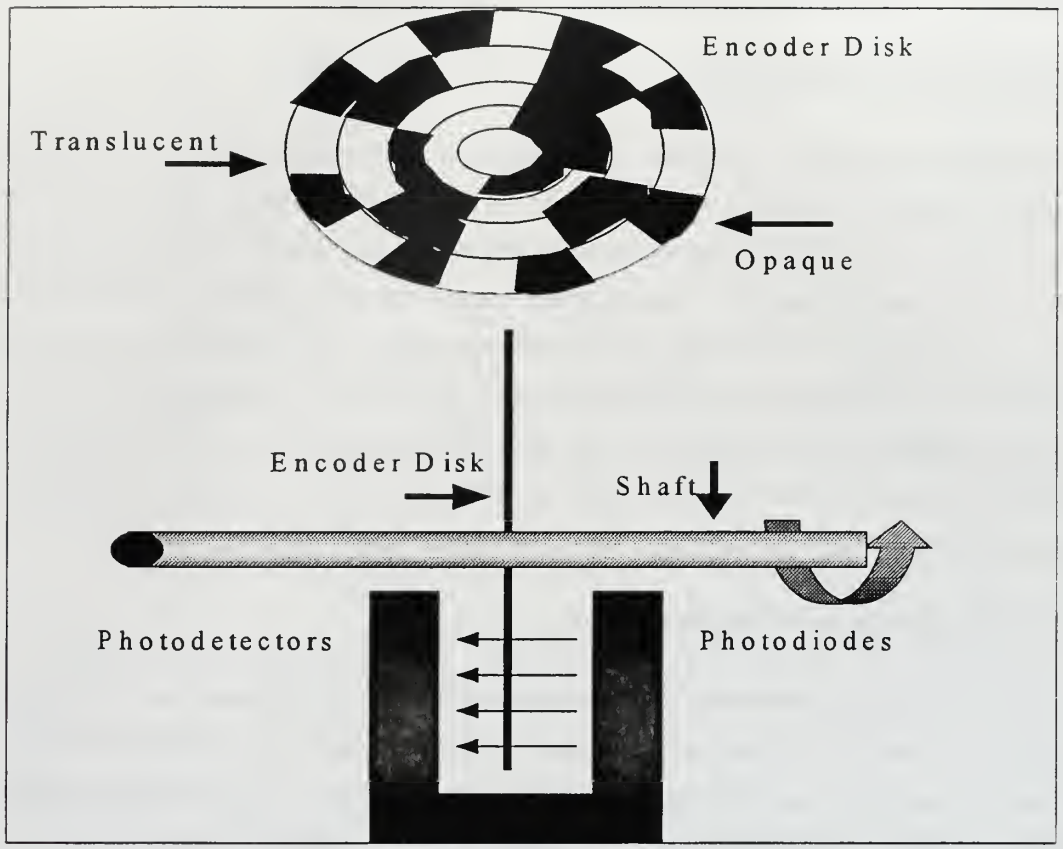

Figure 4. Optical Shaft Encoder After Ref. [2]

underneath the disk along the radius of the disk. As the code rotates, the alternating translucent and opaque sections of the disk, allow the light source to transmit through the disk to the photodetectors. Position angle is determined from the binary code sampled through the photodetectors. Higher resolution is obtained by adding more code rings. [Ref 2.]

E. DATA ACQUISITION SYSTEMS

Sensors such as the CCDs or thermisters provide the means by which phenomena are measured. From these sensors, voltage or current is generated in proportion to the

stimulus. This voltage or current signal must now be processed to provide data for further analysis by the operator or even the onboard processor. Once analyzed, it will then become information. The process of converting signals into data is called data acquisition. Data acquisition is often taken for granted when describing the overall system, however, it is fundamental to a successful design. Data acquisition systems are found in all spacecraft, and are generally configured with a redundant counterpart. Sometimes referred to as Telemetry Encoder Units, Digital Telemetry Units, or Telemetry Data Units they all serve the same purpose: convert measured signals to data [Ref. 15]. The basic parts of a data acquisition system will now be presented.

1. Multiplexers

Spacecraft have many different sensors onboard. To get the data from any sensor, each individual sensor output must be connected to a common set of hardware that can observe the desired signal. Multiplexers are analog or digital devices that combine several independent lines of data to a single output line (see Figure 5) [Ref. 16]. These

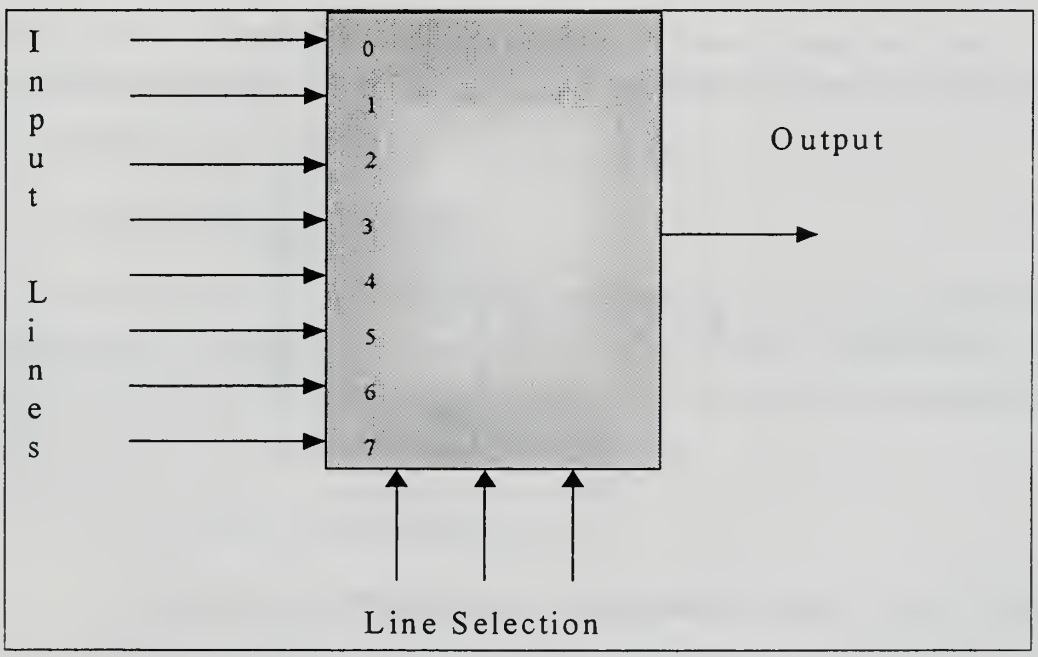

Figure 5. Eight Line Input to One Line Output Multiplexer

input lines share the single output line. An input may pass its signal to the output line only when selected. This is achieved by selection line input on the multiplexer as well. The line selection is easily controlled with the binary decoding relationship:

$$L = 2^n \qquad \text{Equation 4}$$

where L is the number of input lines, and n is the number of selection lines. A separate device keeps track of which input line is next to pass its signal to the output line. As a line selection example, the first line in Figure 5 would be selected to pass its signal to the output if none of the selection lines were active, eg. 000 = 0. If only the first two selection lines were active, 110, then line 6 would be active. Multiplexers can have any number of inputs, the only requirement being that adequate number of selection lines be included to select all the inputs [Ref. 16].

2. Sample and Hold Circuits

Once the signal channel is selected by the multiplexer, the signal passes to a sample and hold circuit (SAH) as appears in Figure 6 [Ref. 2]. These circuits track the

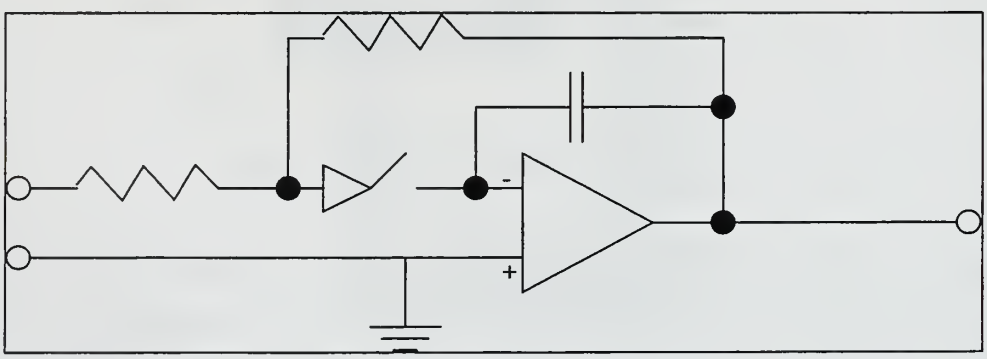

Figure 6. Sample and Hold Circuit Configuration After Ref. [2]

incoming signal and when commanded, hold the last value for a predetermined amount of time. Then the circuit returns to the track mode and repeats the process. Sampled values are stored in an integrating/storage capacitor until released. Due to imperfections in the electrical devices used in SAHs, they are rated by several characteristics. Speed of signal

acquisition is the primary means of rating these circuits [Ref. 2]. This is the time required for the capacitor to charge to full value and remain within a specific error band. Average circuits will acquire a voltage in a ±10V range within 0.01% within several hundred nanoseconds to one microsecond [Ref. 2]. Hold mode droop is a second characteristic. It describes the drop in voltage over a specific time period of the held value while in the hold mode [Ref. 2]. Values for good SAH circuits range between 0.01μV/μs to 100μV/μs [Ref. 2]. Aperture delay is the time from when the hold is commanded to the time the switch is electrically open, thus storing the value. This defines how close to the desired instant the hold is executed. Typical values for this quantity range between under 100 nanoseconds to a few nanoseconds [Ref. 2]. Aperture jitter is the variation in aperture delay from sample to sample. Values of a few nanoseconds to 100 picoseconds are common [Ref. 2]. Interestingly, this value can limit the maximum frequency that can be sampled. Maximum frequency is given by:

$$f_{\max} = \frac{1}{T_A \cdot \pi \cdot 2^{n+2}} \qquad \text{Equation 5}$$

where T_A is the aperture jitter time, n is the number of bits used for quantization in the analog to digital conversion. [Ref. 2]

3. Analog to Digital Converters

The final process to convert a signal to data is the conversion of the analog sample to a digital sample. Analog to digital converters (A/DC) come in many different forms and current technology provides for implementation on a single chip. The configurations most often used in spacecraft design will be presented.

a. Successive Approximation ADC

The operating principal is to synthesize the input signal within the converter itself, then use this replica to cancel out the input signal (see Figure 7). This ADC is designed to perform the quantization within n clock cycles, where n is the number of bits in the output value. Each clock cycle, the ADC adds a fraction of the fullscale value to the previous value. The resulting sum is compared to the input sample voltage. If the sum is less than the input, this last fraction is retained otherwise the last

rejected. Typical conversion speeds for 18 bit converters are on the order of 1 to 3 μs [Ref. 2]. Serial and parallel outputs are also selectable depending on the manufacturer. Additionally, the range of precision is also selectable from 8, 10, or 12 bits.

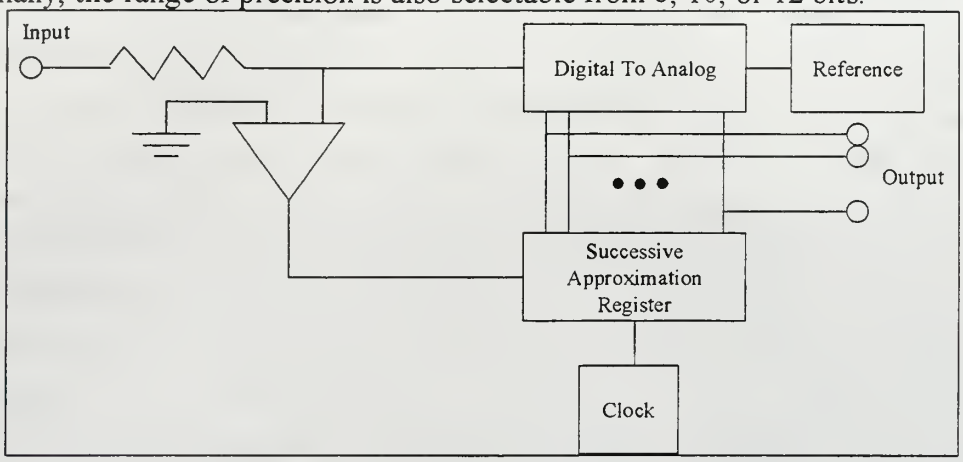

Figure 7. Successive Approximation ADC After Ref. [2]

b. Parallel ADC

These devices are used most often in high speed applications such as video processing because it allows a complete conversion in a single clock cycle [Ref. 2]. The larger number of circutry components is the key to this device. A series of operational amplifier comparators, a precision voltage divider circuit, and a decoder make up the configuration of this device (see Figure 8). The comparators respond high if the input signal is above the voltage drop at the divider network node. This technique allows eight bit conversions to be executed at 20 million sample per second rates[Ref. 2].

The first step in any communications system is to have data to communicate. The data acquisition system collects, formats, and organizes spacecraft data that must be communicated. Each of the subsections in this chapter described the necessary components for generating spacecraft data. Transducers convert the phenomena of interest into a measureable signal. An analog multiplexer combines several channels into a single output. The single output channel is then sampled by the sample and hold circuit. Finally, the sampled signal is converted to a digital value and sent to an output buffer for

further analysis or transmission. A summary slide is in order which ties these components into a system (see Figure 9).

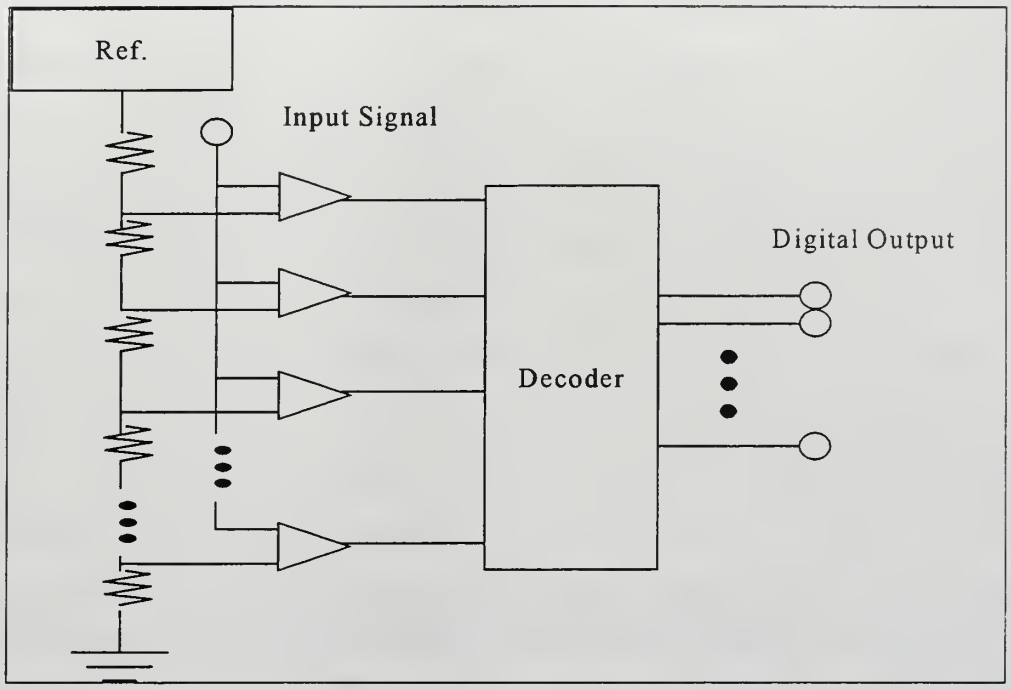

Figure 8. Parallel ADC After Ref. [2]

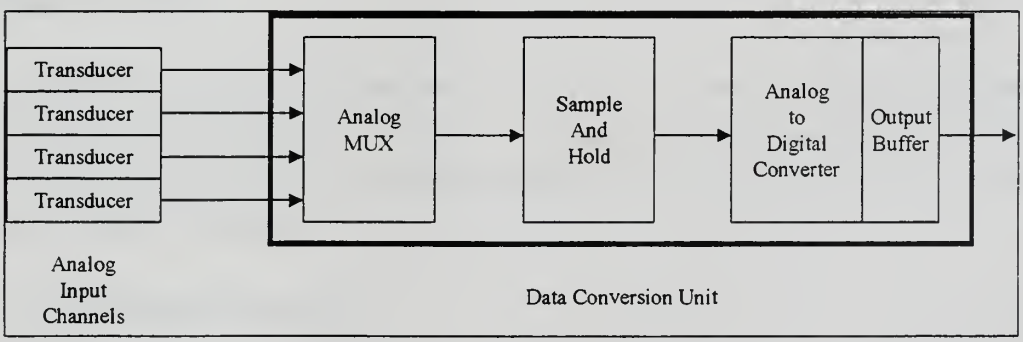

Figure 9. Data Acquisition System After Ref. [2]

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IV. COMMUNICATIONS

Sending and receiving data is the essence of communications. Data is collected and organized by the data acquisition system. Now that data exists, the transfer of that data must be completed. Data communication is performed by the transponder in the spacecraft [Ref. 16]. To ensure successful communications, several decisions must be pre-arranged. Just as though two people were speaking together, language and volume must be compatible. If the two are speaking different languages, they do not understand each other. If one of the two is speaking too softly, the other does not hear anything. And finally, if one person becomes distracted and loses their train of thought, they typically miss some of the conversation. They have simply lost their place in the discussion, and must get back on track with the flow of ideas being expressed. All these ideas can be adapted for spacecraft communications as well. Language can be thought of as modulation. Volume can be thought of as power, and the link budget is a tool used to ensure the power level is not a risk of being too low. Finally, timing and synchronization provide a means for the ground segment to keep track of where the spacecraft is in its communication flow [Ref. 4]. Because the receiving end of the communication system is typically the more critical, all illustrations refer to it, however, it is not difficult to simply put the same illustrations in reverse to derive the transmitting end of the system.

A. MODULATION

Modulating a signal requires several choices to be made. Each is a fundamental part of the communication system design. An important aspect, which must be decided early on is the frequency selected which will ulitmately carry the data. This is also termed the carrier frequency [Ref. 4].

1. Frequency Selection

Many different media for communications exist, however, radio frequencies are most often used in spacecraft TT&C design. Specifically, radio frequencies (RF) in the microwave range from 1000 MHz to 40 GHz are used due to the acceptable transmittance of the Earth's atmosphere for these frequencies (eg. transmittance ≈ 1). Beyond 40 GHz, atmospheric water, oxygen and other molecules severely degrade the transmittance

through the atmosphere [Ref. 17]. Frequencies below 1000 MHz are severely affected by ionospheric scintillation, resulting in distortion in amplitude and phase of the signal. Also, the high degree of confidence required for satellite comand and control prescribe the use of RF wavelengths versus shorter wavelengths (eg. optical (lasers), infrared). When designing the TT&C communications subsection, it is useful to know whether any pre-existing ground segment will be used to operate the spacecraft. If this is the case, the frequency band used will already be defined. Table 1 displays uplink and downlink frequencies used for some currently available satellite control networks [Ref. 1]. With the range of frequencies defined, one part of the language has been decided on.

Modulation of the RF carrier frequency is the actual mechanism of communicating information over a TT&C link. Digital communications, the most widely used communications technique in use today, utilizes a finite symbol set or alphabet. In the case of binary modulation the alphabet set consists of 1 and 0.

Table 1. Existing Satellite Network Uplink/Downlink Frequencies After Ref. [1]

Network	Uplink (GHz)	Downlink (GHz)
Air Force (AFSCN)	1.76 - 1.84	2.2 - 2.3
NASA Deep Space (DSN)	2.025 - 2.120 7.145 - 7.190	2.2 - 2.3 8.4 - 8.5
Intelsat/COMSAT	5.92 - 6.42 14.0 - 14.5	3.9 - 4.2 12.2 or 17.7
Tactical Data Relay System (TDRS)	2.1064 MA* 2.025-2.12 SA** 13.775 SA**	2.2875 MA* 2.2 - 2.3 SA** 15.0034 SA**

MA* - Multiple Access, 20 simultaneous users

SA**- Single Access

Modulation, however, must be analog, because the communications media require it. So the techniques employed in modulation are a way to produce digital results using analog techniques. Analog signals, sine and cosine, are used in such a way to obtain a

digital representation by exploiting their characteristics. Two different frequencies, for example, can be used to represent a bit one or a bit zero. Manipulation of the phase of a sinusoid is also a good option. That is, when the phase changes by 180°, we can interpret the change as a change to a different bit. The frequency method is much easier to implement, giving it a large degree of robustness, but it has limits in performance [Ref. 16]. Implementing phase detection hardware is much more complicated, but yields greater performance. Figure 10 displays the more common modulation types used in satellite communications and their associated wave forms.

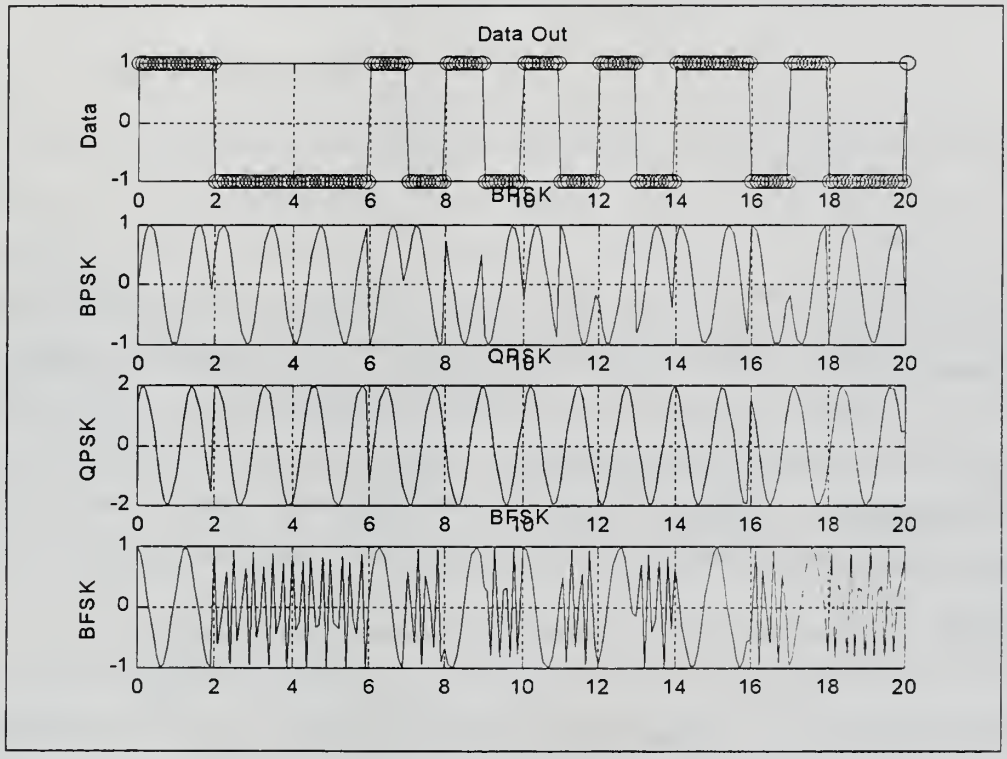

Figure 10. Common Modulation Waveforms in Satellite Communications

2. Bit Error Rate

Digital communications system performance is rated according to the probabililty of making an incorrect decision for any bit being received [Ref. 4]. This probability of bit error, P_B, is a measure based on the statistics of the bit stream given the probability of a bit one, probability of a bit zero, probability of choosing bit one given a bit zero was sent and

$$P_B = P(s_1)P(s_2 \mid s_1) + P(s_2)P(s_1 \mid s_2) \qquad \text{Equation 6}$$

where s_1 is symbol one or bit one, s_2 is symbol two or bit zero, $P(s_1)$ is the probability of a bit one, $P(s_2|s_1)$ is the probability of choosing bit zero when bit one is sent. Note that when the channel is symmetric, or when the probablility of a bit one is equally likely to be a bit zero, and that the probability of symbol one given symbol two is the same as its complement, then the equation simply becomes:

$$P_B = \frac{1}{2}P(H_2 \mid s_1) + \frac{1}{2}P(H_1 \mid s_2) = P(H_2 \mid s_1) = P(H_1 \mid s_2) \qquad \text{Equation 7}$$

3. Noise

The statistical nature of the calculation is a direct result of the noise from the transmission channel. Noise is by nature random, and subsequently is unpredictable. Since noise is added to the signal at the receiver, its random effects must be accounted for, thus each detection of the signal becomes a random variable. In most cases, the noise can be considered a Gaussian random variable [Ref. 4]. That is, the noise has a probability distribution function that is described by a gaussian distribution which is defined as:

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty \exp(-\frac{u^2}{2})du \qquad \text{Equation 8}$$

where Q(x) is the complementary error function or co-error function and is commonly used to describe the probability under the tail of the Gaussian distribution. The co-error function is not evaluated in closed form, and typically tables or approximations are used to evaluate its arguments. One such approximation is valid for the argument greater than three (x>3) and is written:

$$Q(x) \approx \frac{1}{x\sqrt{2\pi}} \exp(-\frac{x^2}{2}) \qquad \text{Equation 9}$$

Note, for most analysis with noise, the random variable is taken to be zero mean and unit variance. Then adding the average power provided by the bit one or bit zero simply changes the mean of the random variable. Bit one drives the mean positive and bit zero drives the mean negative (we implement bit one as positive voltage and bit zero as negative voltage in the receive equipment). [Ref. 4]

4. Signal to Noise Ratio

One final definition is the Signal to Noise Ration (SNR). This is simply the a comparison of how much signal power exists relative to the noise power. For understanding, more signal power ensures less liklihood of making an error when deciding whether bit one or bit zero was sent. Typically this quantity is described as the energy in one bit divided by the energy in the noise for the same time interval (Eb/No). This can be shown with the following equations:

$$\frac{S}{N} = \frac{2 \cdot Ac^2}{N_o \cdot T_{bit}} = \frac{2 \cdot Ac^2 \cdot T_{bit}}{N_o} = \frac{2 \cdot E_{bit}}{N_o} \qquad \text{Equation 10}$$

where Ac is the amplitude of the transmitted signal typically in volts, Ac^2 is the power of the transmitted signal, No is the noise power in one bit period typically in volts^2/Hz, T_{bit} is the duration of one bit period typically in seconds, and 2 is a coefficient used to simplify calculations. [Ref. 4]

The primary measure of performance for digital communication systems is the probability of bit error (P_B). Comparative analysis shows that it is desirable to have the lowest P_B for a given SNR. Figure 11 displays the plot of the various P_B versus Eb/No.

In practice, a system is designed by choosing a modulation scheme that meets the required probability of bit error. For example, most communication systems require P_B to be at least 10^{-5} for quality communications, or one bit in error for 100,000 bits transmitted [Ref. 4]. Recall that Eb/No was derived from the signal power. This directly affects transmitter power. Greater Eb/No requires greater transmit power. For a satellite

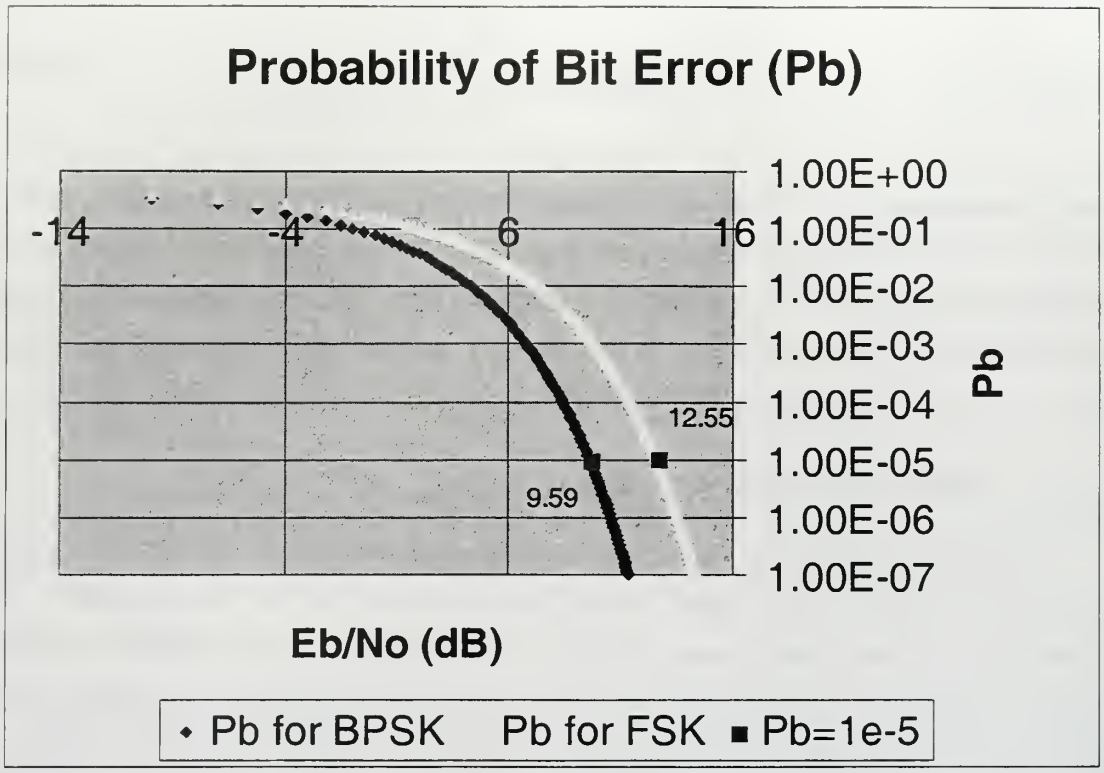

Figure 11. Probabitly of Bit Error (P_B) vs. Eb/No for Various Modulation Schemes

power onboard the spacecraft is a valuable and limited commodity. Good design strives to minimize the required transmitter power while maximizing the robustness. Choosing BPSK, since it requires the least Eb/No we have:

$$P_B = 1 \cdot 10^{-5} \Rightarrow \frac{Eb}{No} = 9.59dB \qquad \text{Equation 11}$$

Table 2 provides information regarding modulation schemes chosen by common satellite communications networks [Ref. 1].

B. LINK DESIGN

Explicitly defining the communication link characteristics comprises the essence of the link budget design. This calculation defines the system communication performance in tabular format, and is an essential element in any communication system

Table 2. Modulation Schemes for Common Communication Networks After Ref.[1]

Network	Uplink Modulation	Downlink Modulation
AFSCN	FSK	PCM/BPSK/FSK
DSN	PSK/FSK	PCM/PSK/PM
TDRS Cross-link	QPSK/Spread spectrum	QPSK/Spread spectrum

FSK = Frequency Shift Keying BPSK = Bi Phase Shift Keying PM = Phase Modulation

PCM=Pulsed Code Modulation QPSK = Quadrature Phase Shift Keying

design [Ref. 1]. This tabular calculation is an alternate representation of the link equation:

$$M[dB] = EIRP[dBW] + \frac{Gr}{T}\left[\frac{dB}{K}\right] - \left(\frac{E_{bit}}{No}\right)_{rqrd}[dB] - R\left[dB - \frac{bits}{\sec}\right] - \kappa\left[\frac{dBW}{K - Hz}\right] \cdots$$

$$\cdots - Ls[dB] - Lo[dB] \qquad \text{Equation 12}$$

where bracketed terms are units, EIRP is the effective isotropic radiated power, Gr is receiver antenna gain, T is receiver temperature, $(Eb/No)_{rqrd}$ is defined by the modulation scheme chosen, R is bit rate, κ is the Boltzmann constant (228.6 dB), L_s is the path loss, and L_o is the implementation loss [Ref. 4]. Note that all terms are in decibels which is determined from the following equation:

$$X[dB] = 10 \cdot LOG_{10}(x) \qquad \text{Equation 13}$$

1. Effective Isotropic Radiative Power

Considering any transmitter/receiver pair, an initial assumption of an ideal isotropic radiator is made. This source transmits RF uniformly over 4π steradians. Power density at some distance d from this source is directly proportional to the transmitted power, and is written:

$$p(d) = \frac{P_{transmit}}{4 \cdot \pi \cdot d^2} \qquad \text{Equation 14}$$

where $P_{transmit}$ is the transmitter power, and d is the distance from this radiator. Placing this radiator at the focal point of a parabolic curved plate or dish will change this power density such that the concave side of the dish concentrates the flux in one direction. The

increase in power due to the concentrating effect of the concave dish or directive gain is described by :

$$G = \frac{\text{maximum power intensity}}{\text{average power intensity over } 4\pi \text{ steradians}} \qquad \text{Equation 15}$$

This relation can be utilized to describe a radiator, which if isotropic, would have power EIRP:

$$EIRP = P_{transmit} \cdot G_t \qquad \text{Equation 16}$$

Additionally, the antenna gain, G, is related to the antenna effective area by:

$$G = \frac{4 \cdot \pi \cdot A_{effective}}{\lambda^2} \qquad \text{Equation 17}$$

where λ is the wavelength of the carrier frequency, and the relation only holds for $A_{effective} >> \lambda^2$. [Ref. 4]

2. Receiver Sensitivity

This quantity has been defined as the receive antenna gain divided by system thermal temperature (K). It is a good description of sensitivity for two reasons. Since thermal noise is the primary noise source limiting the satellite link it is designed to be as small as possible. Due to mass and pointing limitations, the antenna gain is also bounded. Thus for a given antenna size, and thus fixed power flux density, the only way to increase receiver sensitivity is to decrease system thermal noise. This is typically done with low noise amplifiers located directly on the back of the antenna. Additionally, by defining this quantity in two terms, Gr and T, system tradeoffs can be made with a great deal of flexibility. [Ref. 4]

3. Bit Rate

Simply the rate at which data will be transferred across the link. Note that if any forward error correction coding is used, this quantity will be reduced. Intuitively, the

link equation shows that when bit rate is increased, total margin is decreased. Thus all else being equal, there is less liklihood of bit errors with slower data rate.

4. Boltzmann Constant

The Boltzmann constant is defined as $1.38*10^{-23}$, or –228.60 dBW/K-Hz, and is a direct result of the definition of thermal noise power:

$$N = \kappa \cdot T \cdot W \qquad \text{Equation 18}$$

5. Path Loss

Free space path loss is given by:

$$L_s = \left(\frac{4 \cdot \pi \cdot d}{\lambda}\right)^2 \qquad \text{Equation 19}$$

This is the loss proportional to distance squared suffered by electromagnetic radiation. Note, this loss is inversely proportional to frequency, however, the atmospheric transmittance bounds the highest frequency to approximately 50 GHz. This is the largest loss to account for in the margin calculation [Ref. 4].

6. Other Implementation Losses

Smaller losses exist, and are important for accounting purposes. Imperfections in filter design (2-4dB), rain attenuation of the signal (2-3.5dB), polarization losses (0.25dB), and pointing losses (3-5dB)are typical of this combined value. Typical values range from 12 to 15 dB [Ref. 4].

7. Margin

Margin is the be all end all of the link budget design [Ref. 4]. All system trades should produce at least 3dB of margin for conservative design. When all loss and gain terms are known well, it may be possible to have a margin of exactly 3dB. Otherwise something greater than 3dB is common.

8. Power Flux Density

For the spacecraft downlink, this term is limited by Federal Communication Commission law. This quantity is limited to −148dB per 4KHz channel or less. If this value is exceeded, special permission must be requested from the FCC to ensure minimal interference with other RF users when operating.

C. DEMODULATION

Once modulated and carried across the channel, the modulated data must be demodulated. Hardware known as the receiver is used to perform this action. In general, a correllator element followed by an integrator are found in today's receiver structures. This allows sufficient recovery of a baseband waveform which is then sent to a comparator for conversion to TTL levels by a comparator amplifier. Specific receiver structures are required depending on the choice of modulation. BFSK will be presented, followed by the BPSK receiver.

1. BFSK Receiver Structure

Since BFSK utilizes two tones to transmit information, two banks of correlators are required to demoduate the signal. One bank, with both an inphase and quadrature phase for noncoherent BFSK, appears for each tone. For one bank, and each phase, the incoming signal is heterodyned with a replica of one of the tones.

The resulting signal, which has a component at baseband or f_c=0 Hz, and a component at f_c=2f_c, is sent to an integrator. The integrator has a low pass filter characteristic which removes the terms above one bit rate, such as the terms at twice the carrier frequency, and passes the baseband term. Due to the lack of phase knowledge, a square law detector is used to recover the baseband signal. The equations depicted carry out the mathematical expresions for the correlation demodulator. Figure 12 shows the noncoherent BFSK receiver in graphical format. Once baseband is recovered, the signal is sent to a comparator which simply converts the received voltage to a stream of square pulses at ±1 volt.

$$s(t) = \sqrt{2}A_c \cos[(2\pi f_c \pm \frac{\Delta f}{2})t + \theta_0] + n(t)$$

note that n(t) is Additive White Gaussian Noise

$$r(t) = s(t) \cdot 2\cos[(2\pi f_c + \frac{\Delta f}{2})t]$$

$$= 2\sqrt{2}A_c \cos[(2\pi f_c + \frac{\Delta f}{2})t]\cos[(2\pi f_c + \frac{\Delta f}{2})t + \theta_0] + 2n(t)\cos[(2\pi f_c + \frac{\Delta f}{2})t]$$

$$= \frac{2\sqrt{2}A_c}{2}\{\cos[(2\pi f_c + \frac{\Delta f}{2} + 2\pi f_c + \frac{\Delta f}{2})t + \theta_0] + \cos[(2\pi f_c + \frac{\Delta f}{2} - 2\pi f_c - \frac{\Delta f}{2})t - \theta_0]\} + \cdots$$

$$\cdots + 2n(t)\cos[(2\pi f_c + \frac{\Delta f}{2})t]$$

$$= \sqrt{2}A_c \cos[(2\pi 2f_c + \Delta f)t + \theta_0] + \sqrt{2}A_c \cos(-\theta_0) + 2n(t)\cos[(2\pi f_c + \frac{\Delta f}{2})t]$$

Integrating this expression removes the $2f_c$ term and the f_c term as long as $f_c >> R_b$, note that θ_0 is a uniform random variable $[0,2\pi]$.

$$X(t) = \frac{\sqrt{2}A_c}{T_b}\int_0^{T_b}\cos(-\theta_0)dt = \frac{\sqrt{2}A_c}{T_b}\cos(-\theta_0)\int_0^{T_b}dt = \sqrt{2}A_c\cos(-\theta_0)$$

which gives a single term at baseband which will then be squared and compared.

2. BPSK Receiver Structure

Since BPSK modulation associates a bit one with one phase, and bit zero with another phase, the receiver requires phase coherence. Unlike the BFSK receiver which does not require any knowledge of the carrier phase, phase coherence, or precise knowledge of the carrier phase, requires additional circuitry which complicates the hardware. Phase knowledge can be obtained from a phase locked loop circuit or Costas loop which aquires and tracks the phase [Ref. 16]. Once attained, the resulting signal is heterodyned with a replica of the carrier frequency. This heterodyning generates a signal with terms at baseband and at $2f_c$, not unlike the BFSK receiver since both use correlator demodulator structures. An integrator then removes the term at $2f_c$, due to its low pass filter nature, and the baseband signal is passed to a comparator for conversion to the stream of square pulses. Figure 13 shows the graphical structure of the BPSK receiver.

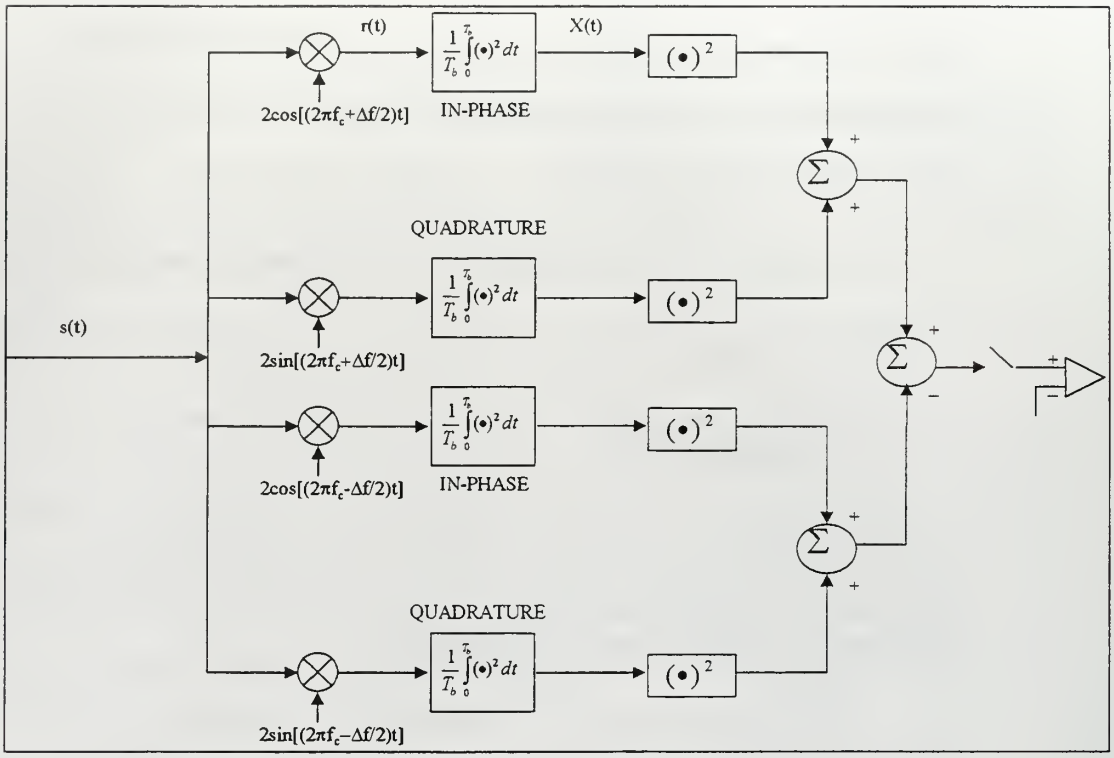

Figure 12. Non-Coherent BFSK Receiver Structure

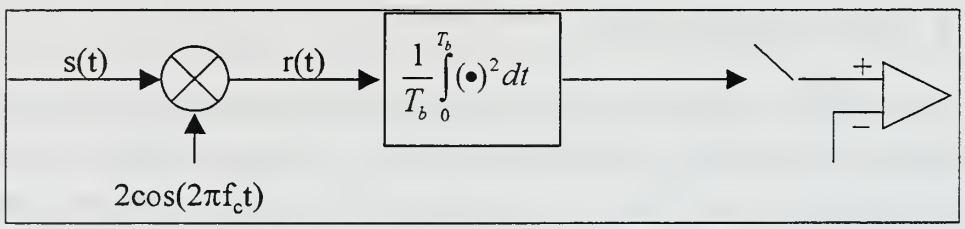

Figure 13. BPSK Receiver Structure

D. TIMING AND SYNCHRONIZATION

The transmit side of any communication system always knows what data it is sending, what frequency it is utilizing, what the phase of the carrier is, and where in the data frame structure the transmitter is, but the reciever does not have knowledge of any of this. Each of these items must be deduced at the receiver itself, from the signal it is receiving. Additionally, any time the transmitting side is reset, perhaps if the spacecraft

payload experiences an anomaly recovery, or if the ground station is reinitialized, or even if the communications link fails, all this information must be re-established. Of primary importance is: establishing bit synchronization, and establishing frame synchronization.

1. Bit Synchronization

Before any data processing can begin, the receiving system must be slaved to the payload clock. That is, the data stream must be demodulated from the carrier, by the receiver hardware, and the data stream must be identified relative to a timing signal from the spacecraft. The generation of this timing signal is the most critical function of the bit synchronizer [Ref. 2].

a. Clock Extraction Circuits

In general, a synchronized timing or clock signal that exactly transitions with the beginning of a data pulse is desired. Ideally, this should happen as soon as data is received by the bit synchronizer, even when a string of all ones or all zeros occurs. This does not usually happen. Generally, some amount of synchronization time must occur and depending on the type of clock extraction circuit used, the clock signal may get lost.

Open loop extraction circuits are the primarily found in practice. Since no feedback information from previous symbols is taken into account for current clock rate or transition time extraction. They are easily implemented, and provide adequate clock signals as long as the data does not appear as long strings of ones or zeros. Figure 14 shows the structure of an open loop clock extractor. As can be seen in the figure, an image of the data stream delayed by half a bit period is correlated with the data stream. Heterodyning the two signals produces another random bit stream which is characterized by a discrete harmonic at integer multiples of the data rate [Ref. 2]. The bandpass filter isolates this harmonic and passes the harmonic signal through a hard limiter which produces the clock pulse. If the data has a long string of ones or zeros, the heterodyning produces no new bit stream, and therefore no integer multiple harmonic. Thus the clock signal vanishes, also known as loss of lock, until the bit stream alternates ones and zeros again. [Ref. 2]

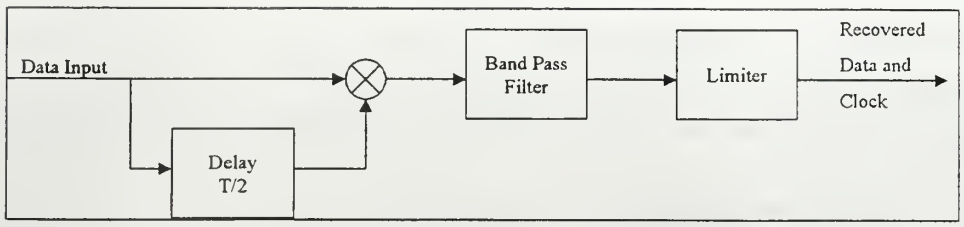

Figure 14. Open Loop Clock Extraction Circuit After Ref. [2]

Closed loop extractor circuits require feedback information to provide the clock rate and transition time. The clock signal is much more robust than that generated by an open loop circuit, however, at the expense of complicated hardware involved and additional time required to initially lock onto the clock signal. Typically, a phase locked loop circuit is used to produce the clock signal. Figure 15 shows the structure of a closed loop clock extractor phase locked loop. The clock signal, generated as the output of the voltage controlled oscillator (VCO), is sped up or slowed down by the difference in two signals. The two signals are generated from the integration over a single bit period. An

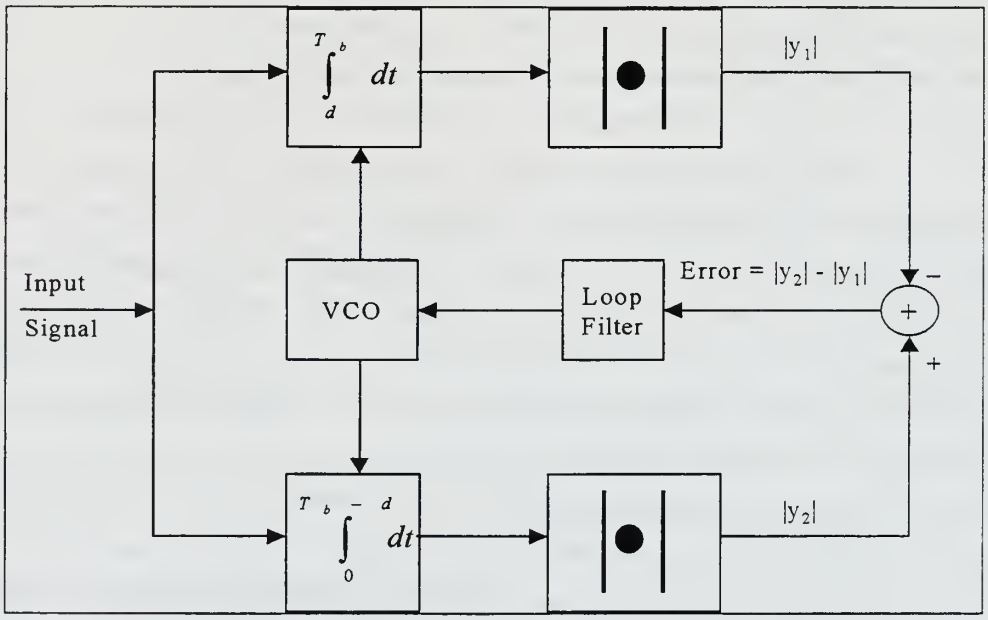

Figure 15. Closed Loop Data Synchronizer After Ref. [4]

example is in order. Data is sent to two integrators, each integrates over a fraction of a bit. The integrations are staggered within the single bit period such that the start of the first integration until the end of the second integration is exactly one bit period. The absolute values of the integrations are then subtracted and the difference used to drive the

speed of the VCO output. If the one integration is larger than the other, a control voltage is generated which appropriately increases or decreases the VCO frequency. This change in VCO frequency affects the integration time of the integrators. If both integrations exactly match, then the VCO is synchronized to the data stream.

b. Data Scramblers

Often interleavers or data scramblers are employed in commercial bit synchronizers to prevent long strings of ones and zeros from occurring. This facilitates employing the open loop extractors with no added complexity. If the data is derandomized at the receiver, it had to be randomized at the transmitter. Thus the randomization of data had to be designed into the system from the beginning. In practice the randomizer is simply a series of shift registers and modulo two adder circuits, see Figure 16, that generate a pseudo random noise (PRN) bit stream when an input is applied. The input is the data stream. Note, the resulting bit stream is pseudo random, not

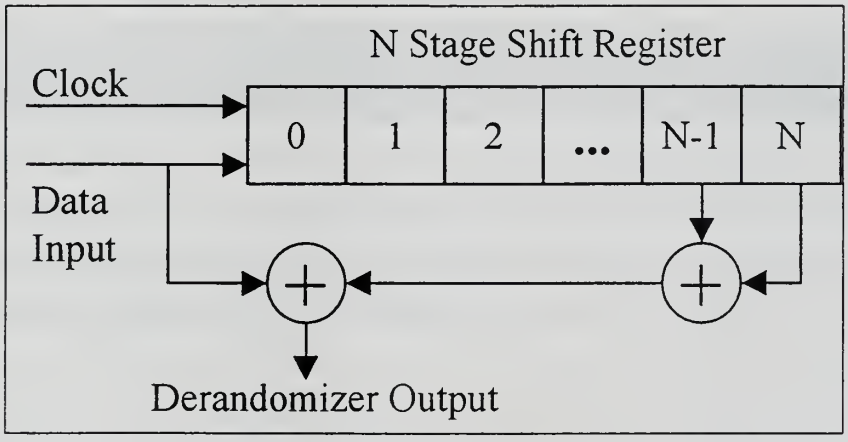

Figure 16. Data Derandomizer Circuit After Ref. [2]

expressly random. That is, the sequence can be recovered with the appropriate shift register/modulo two adder combination. This would not be possible if the resulting stream were expressly random.

2. Frame Synchronization

Frame synchronization requires the receiving system to acquire the spacecraft's data structure. Without first achieving bit synchronization, frame synchronization (frame

sync) is not possible. Three states are typically executed to achieve frame sync: Search, Check, Lock.

a. Search State

Searching consists of correlating the beginning of a minor frame or packet to a particular synchronization marker. This marker is generally a binary word of alternating zeros and ones specifically chosen for its statistical correlation properties. Specifically, the marker must have very low correlation sidelobes, or low values when the word is correlated with a time shifted version of itself [Ref. 4]. The word is also repeated at a specific rate or interval. The receiver correlates the incoming data stream with the known synchronization marker over several intervals, depending on the length of the frame marker, to ensure the correct pattern has been found. If the marker is very short, as in systems where a continuous flow

Table 3. Willard Synchronization Code Words Ref. [4]

Code Word Length [bits]	Sequence
1	+
2	+ -
3	+ + -
4	+ + - -
5	+ + - + -
7	+ + + - + - -
11	+ + + - + + - + - - -
13	+ + + + + - - + - + - - -

of data is present, the number of intervals will be large, translating into a longer acquisition time. Longer length markers facilitate short acquisition times, but increase the amount of overhead in the bit stream. Thus a sacrifice in data rate is required. Long markers are typically required where data traffic is not continuous, or is bursty. Table 3 shows some typical sequences, known as Willard sequences, which have low correlation sidelobes.

b. Check State

Checking consists of locating where in the data structure, major frame, the synchronizer currently is. Considering the case of packet telemetry, this amounts to identifying the packet counter. In a major frame, this is finding the current value of the subframe identifier (SFID) or minor frame number. Once the SFID is located, a check is made to ensure the SFID is incrementing appropriately. If not, the synchronizer will revert back to the search state for reacquisition. If the SFID is incrementing, then frame sync is completed, and the synchronizer moves to the lock state. Note that while in the check state, the synchronization word is still correlated for proper repetition rate and correlation value. Also, while in the check state, commutated and supercommutated data can begin to be processed. This is because this type of data is identified by their relative postions from the SFID. Subcommutated data is identified by specific SFID and its relative position from the SFID, thus it cannot be processed yet. [Ref. 2]

c. Lock State

Once lock is acheived, the SFID location is known as well as the value. This knowledge allows all data to be processed, and the matrix structure of the major frame can now be filled in. Lock state checks include recognizing the synchronization word and its repetition rate, and that subframe ID increments properly. If any one of these parameters is anomalous, the synchronizer will revert back to the check state. If the link is lost entirely, it may revert back to search state for reacquisition. [Ref. 2]

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V. TELEMETRY FRAME CONSTRUCTS AND STANDARDS

Data structure is as important as the means for getting the data to the desired location. Previously, data collection and transmission were presented. However, the ground station, in the case of satellite operations, must have some way of knowing what data is being transmitted. Receiving a long string of numbers does not provide any means for interpreting these numbers. Therefore, some method must be applied to structuring the data into a fashion which allows the receiving station to parse the values into meaningful information. Standard formats which have been previously agreed upon by various users with respect to a group of ground facilities allow interoperability and at the same time can reduce costs. Costs are reduced when several manufacturers develop hardware which comply with the format and thereby increase the supply of available hardware.

A. BASIC FRAME STRUCTURE

The simplest form to arrange data in is a large matrix of values. Each data slot, or matrix entry, is assigned to a specific sensor or data source. This basic structure is often called a frame of data. The entire collection of rows and columns compose a major frame, while the individual rows of data are called minor frames [Ref. 15]. Each minor frame, or row, is made up of a fixed number of words, which are generally a collection of eight or sixteen bits [Ref. 2]. Each minor frame will be made up of a fixed number of bits as well. The first word of each minor frame is usually a synchronization word, which provides a means for the receiver to correctly parse the values being transmitted [Ref. 4]. Major frames are always constructed of an integer number of minor frames. Thus far, each parameter is assumed to be sampled once per minor frame, and so the major frame consists of only a single minor frame. That is, all the data is called commutated data. Actual systems, however, often have some sensors sampled more often than others as well as some sampled less often. Supercommutation refers to data that appears in a single minor frame more than once per minor frame, and is often sampled at a multiple of the minor frame rate [Ref. 15]. Subcommutation refers to data that appears less frequently than the minor frame rate. In general subcommutated data is a submultiple of the minor frame rate [Ref. 15].

Subcommutation and supercommutation require that a specific frame be identified from the data stream so that accurate identification of the data is completed by the ground station. Typically this is done by assigning one column in the matrix to be the frame identification marker (ID) or subframe ID. There can be any number of minor frames per major frame, however, some standards limit the total number available. An example of a major frame is shown in Table 4. Each row of data is transmitted from left to right, and at the end of a row, the next row is inserted consequently placing the rows one behind the other in time. This concept for data transmission is also known as time division multiplexing (TDM), which prescribes a specific time slot to a specific data item.

Table 4. Telemetry Frame Format After Ref. [3]

Synchronization Word	Frame ID	1	2	3	...	Super Comm	...	N-1
Synchronization Word	Frame ID	1	2	3	...	Super Comm	...	N-1
Synchronization Word	Frame ID	1	2	3	...	Super Comm	...	N-1
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
Synchronization Word	Frame ID	1	2	3	...	Super Comm	...	N-1

B. CURRENT STANDARDS : INTER RANGE INSTRUMENTATION GROUP

Airborne systems implemented telemetry systems long before space systems, and therefore the standard for telemetry frame formats was first originated by military range/test facilities [Ref. 15]. The Inter Range Instrumentation Group (IRIG) is a body consisting of members from each of the Department of Defense (DOD) range facilities which provides guidance for operating policy and procedure to ensure each range facility is interoperable with the others. This action attempts to reduce ground system costs by assuring similar hardware interfaces for each system with the ground/test station. The IRIG standard for telemetry systems is IRIG 106.B and can be found on the internet at the Range Commanders Council homepage or via the International Foundation for Telemetering homepage. A brief summary of the highlights of IRIG 106. B will be

presented, however, a detailed examiniation of the document should be made to answer specific questions.

1. Type I Format

A fixed format, called Type I, allows only a fixed minor frame length and no greater than 512 words per minor frame. The word length can be four to sixteen bits per word. While words of different lengths may coexist within the same minor frame, the word length in any position must remain constant. Additionally, 256 minor frames are allowed per major frame, and the maximum bit rate is prescribed at five megabits per second, minimum of ten bits per second. Words are not allowed to be fragmented and format changes are also not allowed. Asynchronous formats and independent subframes are also prohibited. The transmitted bit stream must be continuous and must have adequate transitions to ensure continued bit synchronization. The bit rate is not to deviate from the nominal bit rate by more than a tenth of a percent, and the jitter shall not exceed a tenth of a bit interval relative to the expected transition time. This transition time is derived from the average bit period of the last 1,000 bits. The synchroniztion word must be at least 16 bits, but no longer than 33 consecutive bits. A major frame is defined to be the number of minor frames necessary to complete one sample of every parameter. A frame count word is recommended in each minor frame which must be a natural binary count corresponding to the associated minor frame number. Even with these prohibitions and restrictions, most telemetry systems can be successfully designed. However, some complicated systems may require some additional flexibility. Thus a second type of format is available. [Ref. 15]

2. Type II Format

The type II format requires concurrence of the range involved to ensure interoperability with resident hardware, or to arrange for acquisition of supporting hardware. In essence, everything that was prohibited or fixed in type I is now allowed or may be variable in type II. Table 5 displays a comparison of the type I and type II specifications.

Table 5. IRIG Type I and II Telemetry Specifications After Ref. [3]

Parameter	Type I	Type II
Data bits/Words per minor frame	≤ 8192 bits or ≤ 512 words	≥ 16384 bits or ≥ 512 words
Minor frame length	Fixed	Variability allowed
Fragmented words	Not allowed	Allowed (up to 8 segments)
Format changes	Not allowed	Allowed
Asynchronous formats	Not allowed	Allowed
Bit rate	> 10 bps but <5 Mbps	> 5Mbps
Independent subframes	Not allowed	Allowed
Supercomm spacing	Uniform in minor frame	Even as practical
Data format	Unsigned binary	Other allowed
Word length	4 to 16 bits	16 to 64 bits

C. PACKET TELEMETRY

Packet communication techniques have been widely developed in the computer communications industry. Several formats have developed with one particular format finding wide use today: Transmission Control Protocol / Internet Protocol (TCP/IP). Each transmission format has a basic structure with specific requirements for each field, however all have a general structure which appears in Table 6. Packet communications

Table 6. Basic Packet Structure

Field	Contents
Primary Header	Version number / Source / Destination / Packet Count / Pckt Length
Secondary Header	Acknowledgement / Data Field Length / Options
Data Field	Data
Trailer	Error Check Code (CRC)

has developed out of the need to support multiple users while efficiently using a limited amount of bandwidth, or transmission spectrum. Applying this concept to telemetry systems is the newest area of development in the telemetering field. As seen previously,

the common form of data transmission structure used today is TDM. This is generally considered undesirable because sensors send data regardless of whether the data is meaningful or not. An example is in order. When a heater sensor or battery capacity sensor report that the status is 'Heater On' or 'Battery Charging' when this is the expected response, does this constitute meaningful data? Generally, proponents can be found on both sides of the issue, but from a bandwidth perspective an argument can be made for not transmitting this data since it was expected. That is, if that information, which was expected, was not sent, something else more critical could have been sent instead. Thus packet communications is typically employed to attempt to reduce the amount of wasted bandwidth, or to maximize the available bandwidth to other users. In the telemetering application, users could be considered sensors. Three modes have been identified for packet telemetry transmission: commutated, entropy, and virtual channel.

1. Commutated Mode

Commutated mode is very similar to the standard concept of the minor frame. This instance requires the entire minor frame to become the packet. Some number of sensors have data transported within the shared data field of the same packet. The header addressing contains the subsystem originating identifier for the packet and also timinig information. The system design could be simplified by restricting the commutation rate to ensure each sensor was sampled at the same rate and that each data value within the group was only sampled once, that is no supercommutated data within a packet. [Ref. 3]

2. Entropy Mode

The title of this mode refers to sensors which introduce new data, or data that is not expected to change very rapidly. One example is to have a heater turn on due to a change in environmental conditions. Sensors such as this would ideally send information only after responding to external events. However, operationally, it is also desirable to periodically check the status of such a sensor to verify that indeed nothing has changed beyond acceptable limits. Utilizing this mode has both advantages and disadvantages. Nominal conditions imply that relatively static responses are expected from the sensor and thus lower transmission bandwidth is required. Periodic updates would be the only requirements for transmission. The major disadvantage would result from flooding the transmission channel with updates due to some unexpected problem which changed the

state of several similar sensors. This case requires some form of priority indication for these packets to ensure emergency packets were not delayed, and non critical packets were detained. [Ref. 3]

3. Virtual Channel Mode

A virtual channel is a packet where the entire data field is dedicated to the individual sensor data. The name of this mode has been derived from the virtual channel concept in normal packet communications where two individual nodes are connected by a packet path which essentially behaves as a dedicated circuit channel. This mode would typically pass sampled sensor data over a fixed duration of time. For example, if a sensor sampled at N samples per second and was quantized with M bits per sample then the data field would contain N*M bits, or the fixed duration output of the sensor. [Ref. 3]

4. Advantages and Disadvantages of Packet Telemetry

Some clear advantages to using packet telemetry exist. Due to the highly developed nature of packet techniques in the computer communications industry, existing standards could be used with existing hardware and software drivers, reducing development costs. Additionally, by using existing standards, telemetry systems could possibly interface with standard commercial carrier systems. Error correction and retransmission could be easily implemented as well as prioritization of packets to ensure emergency or critical data be transmitted prior to non critical packets, increasing the reliability of the data link. Flexibility would be the paramount advantage of packet techniques since the system could be tailored to the individual subsystem sending data. This is primarily because data is only transmitted as it is generated, and so does not require packaging until a significant quantity of data is present, or required conditions require transmission. The main disadvantage of packet telemetry is the increased complexity of the system design [Ref. 3]. Additional overhead added to the transmitted data also occupies valuable bandwidth which was not present before; however, an argument can be made for the same overhead existing in the TDM system in the form of redundant data [Ref. 3]. The inherent latency of a network environment is also a problem. TDM allows precise time determination for each data element. In the network environment, associated with packet communications, latency, or delay time between packets, is unpredictable and considered random. At this time there are no practical techniques for implementing

precise time tagging of data packets which ensures ordered recovery. Internet protocol version six attempts to reduce latency for certain mulitmedia applications by prioritizing the packets, however, there will always be some latency and ordered recovery is still not guaranteed. A paradigm shift from the TDM nature of telemetry is required for implementation of packet communications in the telemetry field, which is centered around the prioritization of data. Practicality is the last disadvantage, and applies to small systems that do not allow for much internal processing capability [Ref. 3]. Creating packets requires an enormous amount of processing capability which small systems may not be able to justify through cost or system design complexity.

Packet telemetry seems to be the choice format when the data processing system on board the spacecraft is distributed and there is a need for adaptive changes in the data structure in real time.[Ref. 3] If the changes can be anticipated such that they can be designed into the frame structure beforehand, then frame type telemetry may be the better format.[Ref. 3] Frame telemetry is clearly the more simple design, however, there are proponents for packet telemetry techniques.

D. FUTURE STANDARDS : CCSDS

The Consultative Committee for Space Data Systems is an organization founded in 1982 to promote the use of communication standards to facilitate cross support of member agency hardware in the space field. Currently there are ten member agencies, twenty two observer agencies, and 103 industry partners which makeup the organization. Agency membership is voluntary, and employing any recommendation or standard from the CCSDS is not considered binding on any agency. Traditional development of telemetry resources has resulted in a mission specific tracking network that only provides the lowest level of transport service, that is bit level transport. The primary motivation for standardization of telemetry communications is to allow higher level data delivery services for all systems. [Ref. 18]

The formation of a central organization provides a forum in which challenges and innovative ideas can be presented which are common to space agencies around the world. Past forums have facilitated discussion of advanced telemetering concepts. One such concept which now has become an adopted standard is the CCSDS standards for TT&C: CCSDS Telemetry, CCSDS Telecommand, and CCSDS Advanced Orbiting Systems (AOS). All standards if final form appear as 'Blue Books' while recommendations under

member review are 'Red Books'. Technical rationale, analyses, and guidance concerning the recommendations are 'Green Books'. 'White Books' are preliminary draft recommendations considered in development at the committee or panel level, a panel is made up of several voluntary agency members formed to research and make a recommendation on some issue agreed upon by the majority of members. Updates, or proposed changes to the Blue Books are found as 'Pink Sheets'. All standards and books may be found at the CCSDS homepage, or a CD is available in the NPS Spacecraft Research and Design Center (SRDC) Library. This copy was obtained at the International Telemetering Conference held in October 2000 in San Diego, CA. [Ref. 18]

1. CCSDS Telemetry Recommendation

The layering concept of the Open Systems Interconnection (OSI) network model was the primary blueprint for developing the CCSDS telemetry systems recommendation. In following this existing concept versus developing a new concept and applying it to the complex operational requirements of space data users, a much broader audience is capable of employing the recommendation. Employing an existing model also facilitates manufacture of hardware systems compliant with the recommendation due to the widespread use of the model in commercial computer communications concepts. Figure 17 shows the layers of the OSI model as compared to the packet telemetry employed in the recommendation.

The primary benefits of the packet telemetry based on the layered network model are the increased number of data services available to the user, and dynamic allocation of bandwidth between subsystems or sensors. Additionally, the size of the packets is not constrained, that is, variable packet lengths are supported, and most importantly, they are only created when necessary. Thus the creation of packets by data source processes is optimized to the data source, providing for more efficienct use of the available channel bandwidth. Utilizing the header information of the packets, multiple users may receive only the data of interest, and may choose not to process all the data being delivered. This optimization of ground resources is also an important benefit, and allows distribution of the data units over wide or local area networks.

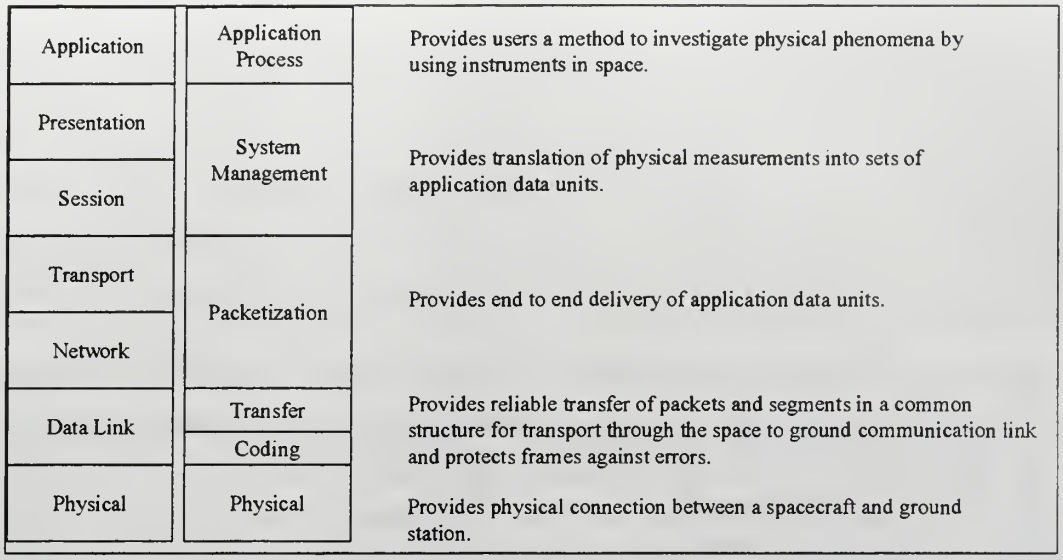

Figure 17. Layered Telemetry Service Model After Ref. [19]

a. Application Process Layer

Essentially this layer does not change from the traditional employment of TT&C systems. This layer is the sensors or payload that converts physical phenomena into measurements. [Ref. 19]

b. System Management Layer

This layer provides translation of the physical measurements into sets of application data. It is comprised of a sampling and quantization process which transforms measurements into data. [Ref. 19]

c. Packetization Layer

The primary unit that is output from this layer, the packet, is created through a process which transforms the application data units from the System Management Layer. Wrapping the application data units with additional data units, header and trailer, the packet is created. The header unit contains source information, packet sequence count, source data, and data field length. In the packet source information, the application process identifier is essentially the address of the data source. The packet

sequence control information includes two bits which determine if the packet is the first in a series (01), a continued packet (00), or the last of packet series (10). Additionally, the source sequence count is also a field in the sequence control information, and allows the recipient of the packet to determine whether a packet has not arrived or was lost in transit. Packet data length allows the recipient to determine exactly how long the packet is. The optional trailer is an error control field. The packet format appears in Figure 18.

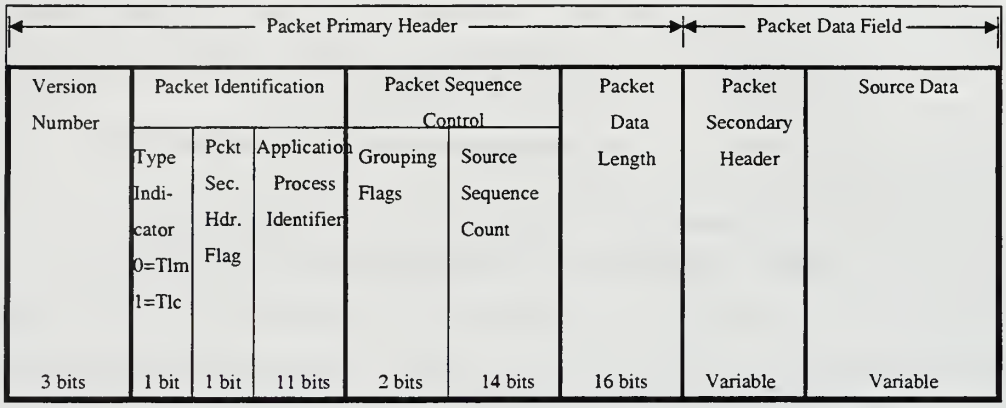

Figure 18. CCSDS Packet Format After Ref. [19]

Not only are data packets an option at this layer, but fill or idle packets are available as well. When the system management layer has no information to send, idle packets are necessary, as this ensures a continuous stream of data for the next layer. This layer provides for end to end delivery of data. [Ref. 19]

d. Transfer Layer

A fundamental structure to any telemetering system, the fixed length transfer frame, is created by this layer which is made up of a variable number of packets or packet segments for transport through the communication link. CCSDS standard provides for a fixed length transport data unit which serves to transport packetized data, and is not unlike the minor frame of the IRIG standard. The primary header contains standard information which identifies the spacecraft, the frame count, and data field status. Additionally, information regarding the concept of virtual channels is also in this header. Virtual channels provide a means of organizing and prioritizing information. The CCSDS standard provides for up to eight virtual channels. These channels are identified by the telemetry system designer prior to implementation. Each channel has a

channel 0, being highest, and channel 111 the lowest. Associating certain data sources or data types to a particular virtual channel and multiplexing them provides support for multiple streams of user data to be shared on the same physical downlink. For example, payload or real time data may be assigned to virtual channel 0 (VC 0), while bus health data may be assigned to virtual channel 1 (VC 1). Thus a single transfer frame may contain several VC 0 data packets. If the health data source has nothing new to send very often, the master frame may contain mostly VC 0 transfer frames with an occasional VC 1 transfer frame interspersed. Thus the need for multi-carrier donwlinks is eliminated, and prioritization of user data is achieved based on latency requirements. Both the master channel frame count and the virtual channel frame count are used to determine sequence errors at the ground station, both are modulo 256. First header pointer tells the position of the first packet header within the transfer frame data field. The frame error control field consists of a sixteen bit cyclic redundancy code and is not required if the Reed-Solomon channel coding is being used. This provides an error detection capability at the frame level. The transfer frame is required to have a continuous stream of data to ensure bit synchronization at the ground station. Thus idle packets (APID = all ones) may be sent within a transfer frame. Additionally, packets may be split between transfer frames of the same virtual channel. The transfer frame format appears in Figure 19. [Ref. 19].

e. Coding Layer

Current techniques in error correction coding provide for significant confidence in error detection and correction. This layer provides protection against errors induced during transmission through the noisy communications chanel. The CCSDS standard recommends an inner convolutional code combined with an outer Reed-Solomon code with block interleaving. The Reed-Solomon code is a (255,223) code utilized for its burst error correction capability, sixteen byte errors for this case. The convolutional code is a rate one half code with constraint length seven, and utilizes the Viterbi soft decision decoder with 3bit quantization. Implementing both codes provides a required Eb/No of 2.2dB for standard probability of bit error (10^{-5}) for a satellite channel. This results in a 7.3dB gain over standard BPSK with no coding. [Ref. 19]

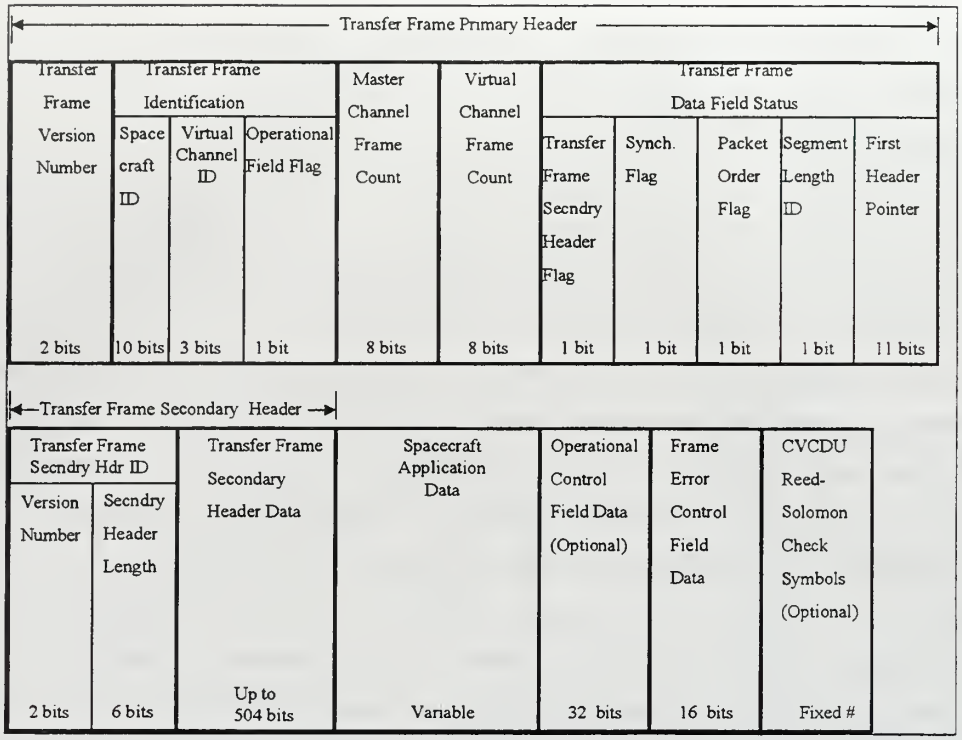

Figure 19. CCSDS Transfer Frame Format After Ref. [19]

f. Physical Layer

Space applications require communications at radio frequency wavelengths. This layer provides for the physical connection through such frequencies between the spacecraft transmitter and the ground station receiver. BPSK is recommended by the CCSDS standard. [Ref. 19]

Each of the layers provides a specific output which satisfies the requirements for that layer. These outputs are shown in Figure 20.

2. CCSDS Telecommand Recommendation

The telecommand recommendation is also based on the layered OSI model. The standard was developed to meet the needs of the conventional mission environment which is typically characterized by the transmission of low rate command data to vehicles of moderate complexity. Figure 21 displays the layered telecommand (TC) service model with outputs. [Ref. 20]

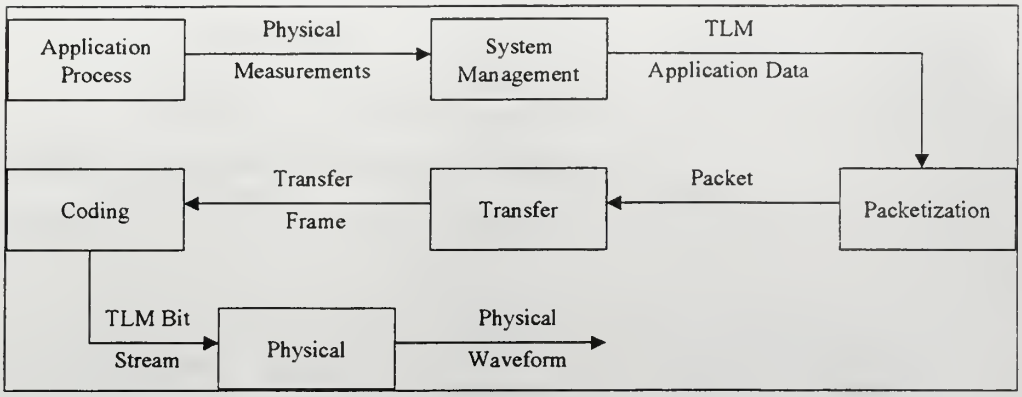

Figure 20. Layered Telemetry Service Model Outputs After Ref. [19]

a. Application Process Layer

Provides the interface between user and processor which allows control of a space mission through the generation, transmission, supervised delivery, and execution of commands. [Ref. 20]

b. System Management Layer

Translates the user command directives into detailed command application data and delivery instructions and manages the end to end delivery.

c. Packetization Layer

Formats the command application data into transportable data units. The packet format of the telemetry recommendation is reused in this layer. Packets generated may be transmitted as standalone entities or may be combined into a larger file entity and transmitted. The application process ID is used to determine where the command is being routed.

d. Segmentation Layer

Breaks the packets into smaller pieces called segments for modular positioning into the data unit of the next lower layer. This unit, the segment, is created by wrapping the portion of the packet with an identification marker and length field. [Ref. 20]

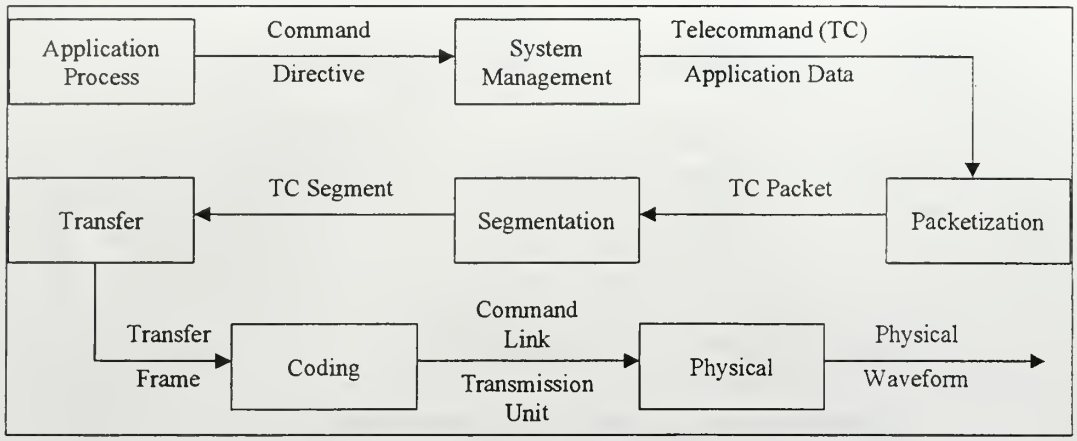

Figure 21. Layered Telecommand Service Model And Outputs After Ref. [20]

e. Transfer Layer

Utilizes the transfer frame concept to transport packets through the channel to the receiving spacecraft. Retransmission procedures are employed in this layer to reliably delver transfer frames to the spacecraft. A closed loop telecommand protocol is utilized to provide a sequential retransmission technique to correct telecommand frames rejected by the spacecraft due to errors. The technique is simliar to the 'go-back-n' technique of the computer communications industry. In this technique, each received telecommand frame is decoded and accepted if the checksum is correct. Then the sequence number of the frame is updated in telemetry via an operational control field of the transfer frame. If the sequence number in memory does not match the expected increasing order, all subsequent frames will be rejected until the expected frame is received.[Ref. 20]

f. Coding Layer

Encodes the user data to protect against noise induced errors during transmission. The transfer frame is broken into blocks which are then coded by a (63,56) BCH coder which can detect 3 bits in error or correct 1 bit and detect 2 bits in error. The fixed length coded blocks are reformatted into a Command Link Transmission Unit (CLTU). [Ref. 20]

g. Physical Layer

Modulates the CLTUs onto the RF carrier and provides necessary procedures to activate and deactivate the channel. [Ref. 20]

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VI. COMMANDING

Maintaining the health of a spacecraft requires the collection of telemetry, trending the performance of onboard equipment from the received data, and making changes to the spacecraft equipment configuration as appropriate. A configuration change can be as simple as turning on a heater, or it could be as complex as reorienting the entire spacecraft for an orbital maneuver. Changes to the onboard equipment can be the result of many factors. Situations where a specific piece of equipment has failed on orbit may require a redundant unit to be called to operation. Failures may also require reprogramming the processor to use remaining equipment in a manner not originally planned for. Some changes may be planned. For example, seasonal changes due to the geometry of the earth and sun in winter versus summer affect the temperature profile for geosynchronous spacecraft. All actions, however, that require changing the configuration of onboard equipment require sending instructions to the spacecraft. These instructions take the form of strings of bits called commands. Commands are generated by the ground, typically by an engineer, executed by an operator, and send to the spacecraft via a combination of hardware and software. Previous chapters have discussed the hardware required to send and receive commands, however, software cannot be neglected. In fact, there is a trend at the present in which several companies are attempting to produce generic TT&C ground software. This initiative to produce a Commercial Off The Shelf (COTS) style of TT&C software is the result of the trend by the government customer to attempt to reduce costs by pursuing products that are readily available in industry. The belief is that by reducing the cost of development and tailored service contracts, overall costs can be reduced. While the argument is interesting and worth studying, this is not the primary objective of this thesis. Instead, by understanding the significance of software, and to some degree what is achieved using the software, one may have better appreciation of the entire satellite system, both ground and space segments.

A. FUNDAMENTALS OF COMMANDING

Commanding systems have become increasingly more important in space systems design due to the increasing complexity of the payloads being launched. The 50 or so commands utilized in the TRANSIT or Navy Navigational Satellite from the 1950s, are of no comparison to the thousands of commands listed for the UHF Follow On

communications spacecraft found in the Spacecraft Operational Database Document. The basic commanding description is not unlike the telemetry description: send data somewhere so that the receiving end can act on that data. However, there are a few differences which are worth noting, and these do affect the system design: command compostion and command strategy.

1. Command Compostion

Previously, the essence of the commanding function was presented in terms of sending data to the spacecraft. The type of data that is sent is really the difference between the telemetry and the commanding subsystems. Telemetry systems generally send a continuous stream of data related to what is happening on the spacecraft. The data has been gathered in real time, formatted for transmission, and then modulated. Commands however are generally shorter strings of data that have been constructed via software based on the available set of commands for the spacecraft. These commands are formed into command words which are made up of specialized fields, not unlike the telemetry minor frame, and are independent of modulation scheme. Generally, there are five separate fields to a command word as depicted in Figure 22.

Initial Timing Mark	Word Synchron-ization	Internal Address	Command Data	Error Check	Final Timing Mark

Figure 22. Command Word Fields After Ref.[2]

a. Initial and Final Timing Mark

These fields are used to identify the beginning and end of a new command word. For the initial timing mark, it also provides synchronization for the payload electronics to lock onto the commanding data stream.

b. Word Synchronization

As in the telemetry case, this field provides a synchronization marker which identifies the beginning of information within the command word.

c. Internal Address

Typically this field identifies which subsystem needs to receive this data so that the action can be taken as defined by the data. This is not unlike a processor memory address.

d. Command Data

The bit representation of the subsystem instruction that is to be performed. This data is constructed by software once an operator enters a command name from the computer console.

e. Error Detection

This field allows a parity bit or series of error detection bits, such as a cyclic redundancy code (CRC), to detect transmission or formatting errors.

Typical command words are much shorter than any telemetry frame. They range from 40 to 100 bits, the error detection/correction field comprising the bulk of the word. With this in mind, it is not inconceiveable to have much slower data rates for the uplink. Uplink rates of two to ten kilobits per second is common. The error detection code is lengthy because of the importance of sending the command once and having it received correctly. For example, if the spacecraft is in an anomaly situation, the opportunities to send commands may be reduced. Thus it becomes critical to send the command once and have it received reliably. A lost opportunity becomes worth the extra overhead of the longer error detection/correction code.

2. Command Strategies

By sending data to the spacecraft, a closed loop control mechanism is achieved. The ground segment operator can send information or instructions to the spacecraft, and view the results of the those actions via telemetry to ensure the correct actions were taken

by the spacecraft. With this closed control loop established, there are three basic strategies used to send and execute commands.

a. Repeat and Execute

This strategy utilizes the concept that an error will not strike twice for the same bit location. Two commands are sent to the spacecraft with no time delay between the two commands. Once received, the command unit compares the two received commands to see if they are identical. If they are identical, the processor executes the commands. If either copy differs at all from the other, then the command is ignored. Reception, execution, and also rejection of the commands would be relayed back to the ground via telemetry. This strategy is typically chosen for command links where a long propagation delay is present, and real time feedback is not appropriate such as in deep space missions.

b. Command, Verify, and Execute

Here, the operator becomes part of the control loop. Once a command is selected and transmitted, it is echoed in telemetry by the command unit. If the operator agrees that the command was received correctly, another command is send which tells the command unit to execute the command. This type of strategy is utilized most often with systems that require burst commanding, and low command rates. Disadvantages to this strategy are the slow rates of commanding when in an anomalous situation due to the operator interface as part of the control loop. Additionally, in this command strategy, some type of timer is implemented in the event that an execute command is not received in a given period of time, the command unit is cleared for a new command.

c. Open Loop Commanding

The simplest form of commanding is also the most dangerous. The open loop allows any command that is received and passes the error detection field check to be executed upon receipt. Obviously, very strong error checking and correcting codes are required for this scheme to ensure damaged commands are not executed. This type of command strategy is chosen for high command rate environments or where long propagation delay is present. It is also used when anomalies need to be corrected.

B. ISCS SOFTWARE FOR FLTSATCOM AT NPS

Now that the basics of commanding have been presented, it is useful to examine a ground system and the software associated with it. The example will be the FLTSAT geosynchronous communications spacecraft which is resident at the Naval Postgraduate School (NPS), Monterey, California. The ground system and software description will be presented to provide an example of an actual TT&C software system implementation. This is not intended to be an in depth description of all the associated equipment and software necessary to conduct operations. It is only a functional overview of the configuration at NPS. More detail is given in the users handbook for each piece of equipment and the suite of ISCS User's Guide manuals located in the FLTSAT Laboratory in Haligan Hall.

1. System Description

The Integrated Satellite Control System, ISCS, is a VAX/VMS based satellite control and monitoring system at the Naval Satellite Operations Center (NAVSOC) in Point Mugu, California. ISCS is a semi-automated system that allows collecting, monitoring and archiving telemetry data, and also has the capability to playback archived telemetry data and to perform trend analysis on the data to monitor the status and performance of the FLTSATCOM and UHF Follow On satellites. ISCS has been modified to allow commanding of the FLTSATCOM spacecraft located at the Naval Postgraduate School in Monterey, California. Currently, ISCS is operational for the FLTSAT satellite using a PCM decommutator, a VAX 4100 microcomputer, a NAVSOC command encoder unit, and an IRIG B timing source. Additionally, the system has two modems which allow remote login by NAVSOC personnel for software upgrade assistance and system troubleshooting assistance.

ISCS consists of three layers of software. The base layer is the Common Environment for Testing (COMET) and the Command And Telemetry System (CATS) which is referred to as COMET/CATS or simply COMET. The second layer consists of COMET applications developed for the Naval Research Laboratory (NRL) at Blossom Point, Maryland. This layer is identified as the Blossom Point or BP utilities. The third layer is NAVSOC-specific software which is either new software or modified versions of the BP utilities.

The COMET software functions as the command, control, and monitoring system of ISCS. COMET is capable of commanding and monitoring satellite operations through

visual displays on operator consoles. It performs real-time telemetry data processing and archives the data for post-operational playback and analysis. The COMET software can do limit and error checking on incoming telemetry parameters through the use of NAVSOC Satellite Verification Tables (NSVT) and display error messages to the satellite operator's, or Duty Satellite Manager's (DSM), COMET console and the ISCS workstation alarm window. COMET can also send commands to a spacecraft. The ISCS menus are especially designed for satellite managers and DSM's to perform multiple satellite operations. The following paragraphs describe the overall functions provided by the menus.

2. Overview of ISCS Menus

The ISCS menus are organized into seven functional groups: COMET, Scheduling, NAVSOC Satellite Verification Table (NSVT), Data Reduction Analysis (DRA), Logon to Another Node, Miscellaneous Functions, and Data Request (DREQ). Those functions which affect the operational ISCS require a personal username and password to be accessed. Different users are assigned different privileges depending upon individual responsibilities. The personal username and password control which functions a user can access and also enable an audit trail to be kept, identifying who used a function and when.

The COMET option initiates a standard COMET console. From the console, a user can issue COMET commands as defined in the COMET Software User's Manuals.

The Scheduling option provides the capabilities to enter or modify a contact, print a hard copy of a contact schedule, and stop and (re)start the scheduler.

The NAVSOC Satellite Verification Table (NSVT) option lets users modify, create, delete, list or print an NSVT. Under this option, users can also send an NSVT to the remote sites via a lease line. Normally, an NSVT is sent to the remote sites automatically when it is created or modified. However, if the automatic send fails for any reason, this option can be used after the problem with the original send is resolved.

Data Reduction Analysis (DRA) is a COMET utility that allows users to create a contact report, look at telemetry points from a user-defined set of telemetry mnemonics, and generate trend plots for long-term state-of-health analysis.

Logon to Another Node allows the user to logon to another node in the local cluster or to logon to a remote site. This option starts the ISCS Menu on the selected

node and then any of the menu functions can be performed. Logging onto a remote site is critical when NAVSOC headquarters fail to receive telemetry data from a remote site, or when the DSM at headquarters needs to monitor site-specific status locally (eg., antenna pointing angles, frame sync status, etc.).

The Miscellaneous functions provide users with the capabilities to send spacecraft ephemeris sets from NAVSOC headquarters to a remote sites (such as NPS), display level 0 alarms, change and manage their personal password, look up ISCS acronym definitions, and set satellite health status.

C. HARDWARE CONFIGURATION AT NPS

The NPS ISCS consists of one VAX4000-100 CPU having 32 MB of memory. This VAX4100 is called FLTSAT for local (NPS) and remote site (NAVSOC to NPS) operations. FLTSAT is connected to the remote sites through a DEC router 700. DECNET software version 6 running on the FLTSAT vax uses the DEC router to handle point-to-point communication between NAVSOC and a NPS. Real-Time-Raw-Change-Only (RTRCO) data can be stored on disk for as long as desired or until memory must be cleared. Additinoally, compressed RTCO (Real-Time-Change-Only) data can be stored on tape. The raw and compressed RTCO data can be analyzed by using the PLAYBACK and DRA utilities.

A DSI PCM Decommutator 7100 is used to demultiplex an incoming multiplexed FLTSAT data stream. The stream is PCM at Transistor-Transistor Logic (TTL) voltage levels. Synchronous FLTSAT data is then transmitted, in time-tagger format, to the frame synchronizer, also part of the DSI Decommutator. The output of the frame synchronizer is transferred into the VAX processor (FLTSAT) via a DRV11-W parallel interface card.

Commands are sent to the NAVSOC Command Encoder Unit (NCEU) via the DEC router at port 1. The NCEU then formats and sends the command to the FLTSAT using BFSK modulation for SGLS frequencies as specified by the AFSCN.

Remote commanding by NAVSOC is accomplished via remote login through one of two modems. These are standard dialup modems using 9.6 kbps data rate, 8 bit words, parity off, one stop bit, and hardware flow control. One modem is connected to the external port located on the VAX 4100, while the other is connected to the DEC router at port 4.

System time is maintained via a True Time IRIG B timing generator/formatter. The clock is connected to both the NCEU and DEC router. See Figure 23 for the NPS operational hardware configuration.

The NPS ISCS has a total of 38 MB of disk storage. This disk space is used for storing VAX/VMS system resources, COMET/applications source and executable files, and archived telemetry data. A software batch program monitors the available disk storage. If the available disk space falls below 20% of the total disk storage, a warning message is sent to the operator.

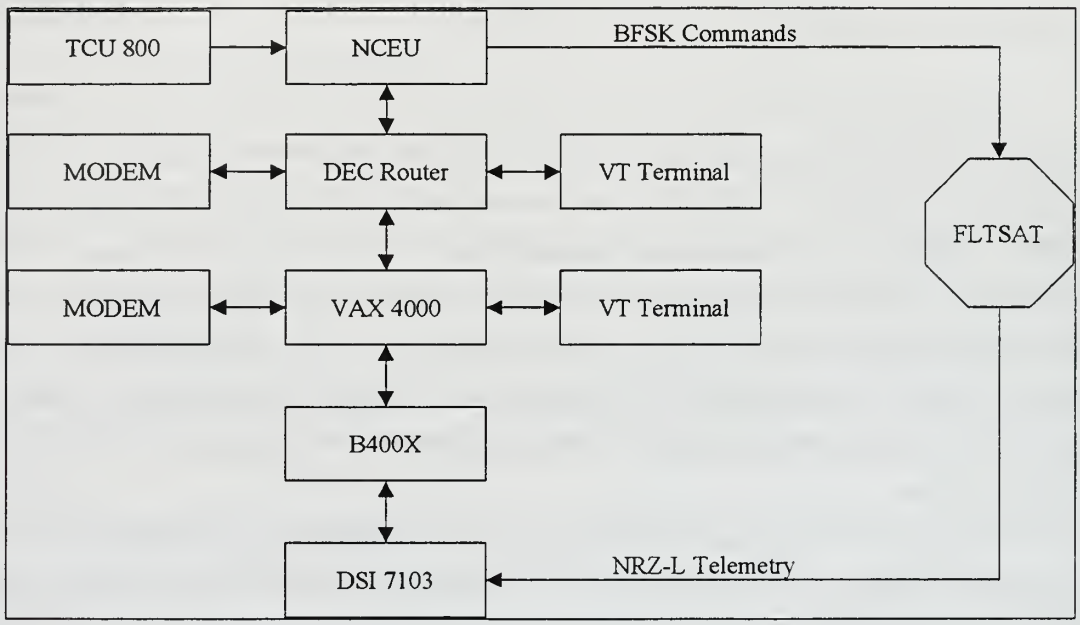

Figure 23. NPS Hardware Configuration

Two VT terminals and a dot matrix printer are connected to the DEC router to: 1) monitor real-time telemetry amd hardware alarms, 2) logon to a remote site for data monitoring and analysis, 3) input keplers to remote sites, 4) display satellite health status, and 5) perform data monitoring and analysis. One TK-85 tape drive, in the expansion box, and a CD ROM drive, in the front panel of the VAX, are installed on the NPS VAX for software upgrade transfer and archived data backup.

D. SOFTWARE CONFIGURATION AT NPS

The ISCS software system consists of four basic components: COMET, Blossom Point (BP) application software, NAVSOC specific software and VAX/VMS operating system & layered products. All four components play critical roles in the performance of ISCS. All NAVSOC specific software is configuration controlled under CMS (Code Management System) at NAVSOC headquarters and are updated at NPS at the convenience of NAVSOC. The following paragraphs detail the functional description of each software component.

1. COMET

The Common Environment for Testing software, also known as COMET, is the command, control and monitoring system of ISCS. COMET performs the commanding and monitoring of satellite operations through visual displays on COMET operator consoles. The structure of COMET is categorized into six different sections: the COMET Shared Image, COMET Executive, COMET Display, COMET Recording System, COMET Graphics User Interface (GUI) and Data Transport System (DTS). For a more detailed description of the COMET software, refer to the COMET user's manuals.

a. COMET Shared Image

The COMET Shared Image region contains COMET shared data. It is a shared region that supports multiple COMET users and all COMET support software.

b. COMET Executive

The COMET Executive is responsible for the scheduling and execution of COMET system services.

c. COMET Display

The COMET Display system is used for the input/output operations between COMET and its operator consoles. This function displays COMET messages and screens and accepts interactive COMET commands at the operator consoles. This function also performs data conversion on telemetry data to engineering units and displays them on the consoles.

d. COMET Recording System

The COMET Recording System allows COMET processes and application programs to record data in a recording file. The prepass perform file specifies the type of data to be recorded and the name of the recording file on a per-pass basis. Once data has been archived, Data Reduction Analysis (DRA) can be run from the ISCS menus to perform data analysis.

e. COMET Graphical User Interface

The COMET GUI allows satellite engineers to display real-time plots on an ISCS workstation for anomaly resolution and analysis. The attributes of a plot can be defined during a contact or with an attribute file before a contact. Three kinds of plots available are: trend plot, scatter plot and histogram. For a detailed description of how to use real-time trending, refer to the "Trend" user's manual.

Furthermore, the GUI software has the capability to alarm, notifiying the operator of any telemetry anomalies. The anomalies are presented both visually and audibly on an ISCS workstation.

f. COMET Data Transport System

The DTS sends and receives messages to and from application software running on the local or a remote VAX.

2. BP Application Software

The Blossom Point (BP) application software includes the Operations & Control (OAC), Antenna Pointing software and Data Reduction Analysis (DRA) Plot Utilities.

The OAC software is composed of two processes (like programs): the OAC Executive and OAC Interface. Only one OAC Executive process can be active per VAX node at any time. Each ISCS site has its own OAC scheduler (OACEXEC). Satellite operators can use the ISCS menu to bring up the OAC Interface process to modify or delete a contact from the OAC Executive.

a. OAC Executive

The OAC Executive handles the processing of scheduled contacts. It can maintain up to 350 scheduled contacts chronologically. The OAC Executive console is only a monitoring console, and the contact schedule can only be modified through an OAC Interface console. When a contact is due, the OAC Executive will call the pre-pass perform file to execute system-specific tasks. When the contact is over, the post-pass perform file will be executed.

b. OAC Interface

The OAC Interface process interfaces with the OAC Executive to provide the capabilities to modify and delete contacts, refresh the OAC Executive screen, shut down the OAC Executive, and issue COMET commands. All COMET commands issued at an OAC Interface console apply to COMET console #1, the OAC Executive console. Multiple OAC Interface consoles can be brought up by using the ISCS menu on different operator consoles.

c. Antenna Pointing Software

The Antenna Pointing software communicates with OAC resources to generate pointing angles. Based on the orbital elements received from NAVSPOC, antenna points (azimuth and elevation angles) are calculated at prepass with a one-minute interval between points.

3. NAVSOC Specific Software

The NAVSOC specific software includes the operations perform files and command procedures, ground station device control software, NAVSOC Satellite Verification Tables (NSVT's), telemetry databases (currently FLTSAT & UFO), ISCS menu system, alert monitoring software, and VAX Virtual Memory System (VMS) specific software.

a. Perform Files

The operations perform files mainly consist of the prepass and postpass perform files. The prepass perform file sets up all telemetry hardware equipment (i.e.

antenna controller, receiver, bit synchronizer, frame synchronizer, and NCEU) during the setup period five minutes before AOS. For a given satellite ID, it also sets up the telemetry link and recording file in COMET to receive data. Last, the prepass perform file submits the post-pass perform file to the COMET queue to be executed at LOS. When the post-pass perform file is executed, it will unlink the telemetry link, close the current recording file and submit the data-ingestion command procedure. At NPS the prepass perform file is executed manually by entering the 'perf link_7.per' command, and executing the post-pass perform file by entering the 'perf unlink_7.per' command.

b. Ground Station Device Control Software

The ground station device control software includes the site-specific software drivers for interfacing with the Antenna Control Unit (ACU), receiver, bit sync and frame sync.

c. NAVSOC Satellite Verification Tables

NAVSOC Satellite Verification Tables (NSVT's) define the upper and lower alarm limits for telemetry items. There are three levels of NSVT's: permanent, temporary and special purpose. Permanent NSVT's can only be generated by an authorized DSM using the "Modify NSVT" menu. The temporary and special-purpose NSVT's are processed at the time of prepass and are only in effect during the pass. A special-purpose NSVT has to be specified by a user when scheduling a new pass.

d. Telemetry Databases

Currently, only the telemetry databases for FLTSAT and UFO are defined on ISCS. Database changes are compiled whenever COMET is re-built or upon special request.

e. ISCS Menu System

ISCS is a menu-driven system designed by the NAVSOC Systems software group. It provides a user-friendly environment for satellite engineers, satellite operators, and DSM's to perform a wide variety of functions.

f. Alert Monitoring Software

The alert monitoring software consists of different routines to provide the capability to receive, display, acknowledge, delete and print alert messages (MUX, DEMUX, telemetry, ground station hardware, etc).

g. VMS System Software

The VMS (Virtual Memory System) operating system controls the ISCS VAX computers in scheduling access to the computer system resources. All ISCS software runs on the VMS operating system. The ISCS software is built upon a privileged environment provided by VMS such that each user's account is given only the minimum privileges needed for performing its tasks.

Several Digital Equipment Corporation (DEC) layered software products are installed in the ISCS system for software development and to provide full functionality of ISCS. These software products are: FORTRAN Compiler, C Compiler, RDB (Relational Database), DECnet, LATCP, Motif and Code Management System (CMS). In addition, SL-GMS (SL Graphical Modeling System), a Commercial-Off-The-Shelf (COTS) software product, is installed on the system to provide the hierarchical graphics capabilities of the Console Graphics software. Also, TEMPLATE, a third-party software package, is used for DRA plotting.

E. COMMANDING OPERATIONS AT NPS

Conducting operations in the FLTSAT Laboratory requires an operator to follow procedures to provide power to the FLTSAT spacecraft, start the ISCS software, configure ISCS for commanding, and then conducting the operations. At this time a checklist is in use to accomplish each of these steps. Copies of these checklists can be found in Appendix F. A brief description of the power up sequence appears in Table 7. Once commanding operations have been concluded, the software must be deconfigured properly and shut down. Then the spacecraft must be powered down. Note that a single battery is always being charged via a trickle charger at 100 miliamperes. The battery is required to successfully provide shore power to the spacecraft.

1. Power Up the Spacecraft

Initially, the battery must first be taken off the trickle charger. It has been observed that the battery has successfully held a charge of 32±1 volt for extended durations (approximately 8 hours) with no charging. Next the trickle charger cable must be disconnected from the spacecraft, and the 'in-flight' jumper cable, W76, must be connected to the spacecraft. Both cables interface at the J-7 connector on the minus X longeron of the spacecraft. Finally comes the power up procedure for the power equipment. The various pieces of equipment are powered up in this order:

Table 7. FLTSATCOM Power Supply Initiation Sequence

Sequence Number	Panel Name	Primary Switch
1	Primary Power Control	Circuit Breakers/ Power
2	Utility Power Supply (P.S.)	Line On
3	Load Array Power Supplies	Line On
4	Charge Array Power Supplies	Power
5	Digital Voltmeter 5900	Power
6	Power Monitor	Power
7	Power Control	Power
8	Telemetry & Commanding Cables	BNC Connections

Once the power equipment is on, the main bus voltage must be increased to 36±1volts. This will be the shore power value applied to the spacecraft bus. Telemetry should be detected at approximately 15 volts. This can be verified at the DSI 7103 panel, if the DSI 7103 is powered on. Lastly, the battery must be connected to the main bus by utilizing the filter conditioning switch and setting the bus enable and tap enable to 'on ' for the A battery. Shore power will now maintain the battery in a trickle charge while providing power to the entire spacecraft. Note, this is only a general discription of the power up procedure. It is not to be used in place of the actual checklist that appears in Appendix F.

2. Start ISCS Hardware

A cold start of the commanding rack of equipment is presented in the checklist in Appendix G. This may not be necessary at each commanding operation. If the equipment is already powered on, then the checklist may be entered at step five: Start ISCS Commanding Software. The sequence for command equipment power up is shown in Table 8.

Table 8. Power On Sequence for Commanding Equipment

Sequence Number	Equipment Name	Power Switch Location
1	VAX Expansion Box BX-300	Front Panel
2	Time Code Generator 800	Front Panel
3	External Modems	Front Panel
4	DECrouter 700	Back Panel
5	NCEU	Front Panel
6	VAX 4000-100A	Back Panel
7	DEC VT Terminals	Screen
8	Printer	Side Panel

3. Configure ISCS Software for Commanding

Once the system hardware has been powered on, a triple chevron prompt (>>>) on the VT terminal should appear. Here a cold boot is in order. By typing 'boot' and return, the welcome message to VAX VMS 7.1 should appear. Entering the user name, ops, and the password, aeronautics, will initiate a COMET session. If a local single chevron prompt is presented (LOCAL>), then the VT terminal is attached to the DEC router. Typing 'C FLTSAT', an acronym for connect to FLTSAT node, and return will attach the terminal to the FLTSAT node (the VAX 4100). Now the COMET sesision may be initiated with the ops/aeronautics username and password.

From COMET, an ISCS prompt will require a personal username/password. NPSLAB(FLTSAT7) or DOGLAW(VMAPR00) should be entered for the ISCS username and password. This authenticates the user of the ISCS Software, and verification will supply a Comet Command Line (CCL) which is identified by the FLTSAT

ops prompt (FLTSAT_OPS>). While in the COMET session, system resources and management functions can be viewed or executed. Typing SHO SYS, show system resources, will display a list of all processes being currently being executed.

To start the ISCS software, '@go' should be typed and return at the FLTSAT ops prompt. All ISCS processes should start, and the message line (line 21 on the screen) should diplay which processes are being started. At the end of this startup, the perform file display line (line 22 on the screen) should display 'EXIT'. At the new CCL, the resource allocation table can be displayed by typing CRT RAT, create resource allocation table, which shows all active telemetry links and VT consoles attached to those links. ISCS is now running.

To begin a commanding operation, the ISCS software must have a link of incoming data. Initiate a link by executing the NPS link perform file: 'perf link_7.per' and return. This perform file initiates a link of incoming data from the DSI 7103 via the DRV 11 card. It also executes the initial configuration of the NCEU, or the transmitter for the system. If the NSVTs are not updated, several errors, called alerts, should occur and will be displayed in the message line. Clearing all of these alerts is required before proceeding. This is accomplished using the clear alert (PF4) and acknowledge alert (PF2) hotkeys. Once the alerts are cleared, the RAT should display console one attached to link 1. Incoming telemetry can now be verified by initiating a telemetry screen: CRT TTC. Subframe ID (SFID) should be incrementing as well as the system time at the top of the screen. Commanding operations can now be initiated.

4. Conduct Commanding Operations

Commanding can only be accomplished by telling the VAX to execute the begin command perform file: bgncmd L=1. This file initializes the FLTSAT commanding software using COMET commands, attaches the console to link 1, brings up a FLTCMD screen, and executes a dummy command to the NCEU. Because there is no cryptography equipment (KIT-223), an error will appear in the message line as an alert. This is a special alert and can only be cleared by the procedure in Table 9.

After verifying telemetry is present, the software must be told to change the command state to 'clear'. This is required since no cyrpto equipment is present, and the spacecraft can only be commanded in clear mode. If it is not changed, the software will encrypt all commands, and the spacecraft will not recognize them. Commanding

operations can now be executed. Currently only two commands are available to send: s1078 Dummy Command, and s0380 AKM Ordnance Safe. A passplan that incorporates all commands that the FLTSAT spacecraft should be able to accept has been developed by NAVSOC and is available in the operator notes in the FLTSAT Laboratory.

Table 9. NCEU Error Continue Sequence

Sequence	Action
1	Press Return
2	Clear the Alert (PF4)
3	Acknowledge the Alert (PF2)
4	Enter 'cont' to continue the perform file
5	Observe 'Command System Reset Occurred' in the message line
6	Press '5' on the keypad to clear the commanding system error flag

5. Deconfigure ISCS

Once commanding operations are completed, the software must be told to end commanding operations via the 'endcmd' statement. This will clear all telemetry from the console. The RAT will still show a telemetry link on link one. This must also be deconfigured. The unlink perform file deconfigures this link: 'perf unlink_7.per'. Finally, terminate all COMET processes using 'term' will stop the ISCS software and leave the user in an idle state which is noted by the FLTSAT ops prompt. This should be the standard non commanding state the commanding system should be left in. It allows relatively quick power up for commanding while leaving the equipment in a convenient and safe configuration.

6. Power Down the Spacecraft

The emergency shutdown procedure is listed at the Power Control Rack and is repeated here. First the digital voltmeter is used to measure the battery voltage and main bus voltage using the selector switch on the Power Control Panel. Next the voltage control knob, also on the Power Control Panel, is turned counter clockwise to match the main bus voltage with battery A voltage. When matched, it is safe to disengage the

battery A tap enable and battery A bus enable switches. Finally, the voltage control knob is turned fully counter clockwise to bring shore power voltage to zero volts. The spacecraft is now disconnected from shore power. Completing the power down requires executing the power up procedure in reverse order.

VII. TT&C SYSTEM FOR A SPACECRAFT

A. INTRODUCTION

The Telemetry, Tracking and Commanding (TT&C) subsystem for the Mithra satellite was designed to meet the requirements of the sponsor as well as any subsequently derived constraints due to other subsystem component implementations. Additional information about specific requirements for the bifocal relay mission and spacecraft design appear in Appendix H. This subsystem design utilizes space proven components in an attempt to ensure the lowest possible risk to the overall bus design, and keep technology costs to a minimum. The TT&C system design included what is traditionally known as the Command and Data Handling (C&DH) subsystem.

B. REQUIREMENTS

Ultimately there were few stated requirements for the subsystem. These included conducting operations via the Air Force Satellite Control Network (AFSCN), minimizing onboard processing, and providing a processor with sufficient capacity to meet Attitude Determination and Control Subsystem (ADCS) requirements. From these requirements the overall TT&C design was tailored in that no ground segment design was required, payload processing could be considered in a separate subsystem, and the processor could be sized for the bus design alone.

1. Derived Constraints

Selection of components or specific characteristics by other subsystems directly imposed requirements on the TT&C subsystem. Utilizing the Air Force Satellite Control Network (AFSCN) for operating this spacecraft allows world-wide coverage to support the mission. Additionally, it imposes strict requirements on the choice of modulation for the uplink and the downlink as well as frequency band. The AFSCN Space-Ground Interface Document prescribes the uplink modulation to be 3-Frequency Shift Keying (FSK) and the dowlink modulation as Bi-Phase Shift Keying (BPSK) [Ref. 6]. S-band is the operational frequency band of the AFSCN, specifically, 1-8 GHz (Gigahertz) to 2.5 GHz. Data rate restrictions are also prescribed by the AFSCN. Maximum uplink channel

capability is 2 Kbps (kilobits per second). Three carriers are available for each downlink channel (1 of 20) through any AFSCN Automated Remote Tracking Station (ARTS) simultaneously [Ref. 6]. These include 128 Kbps, 256 Kbps and 1.024 Mbps (megabits per second) [Ref. 6]. Orbit choice (Circular, 715 kilometer altitude, inclination 40°) defined several key items for operational consideration. The mean payload engagement duration (approximately 4 minutes) as well as the mean AFSCN support duration (approximately 10 minutes) were both prescribed once the orbit was selected. These durations directly impacted the amount of memory required for data storage. Once the orbit was set, analysis was completed to determine the longest outage between AFSCN supports. This was approximately 99 minutes and would also be a driving factor in determining data storage requirements. Pointing and jitter requirements for the Attitude Determination and Control Subsystem (ADCS) require a specific degree of accuracy which must be met by the onboard processor. The ADCS attitude calculations require accuracy on the order of 10^{-3} radians. Thus the processor must be able to accurately calculate these values without loss of needed precision. Regarding the accuracy in pointing the payload, the use of Global Positioning System (GPS) receivers will facilitate refinement of the orbit vector during operations. Each of these constraints further defined the capability and flexibility of the TT&C subsystem (see Table 10).

Table 10. Derived Constraints Summary

Constraint Name	Required Value
Frequencies / Modulation Type (AFSCN)	1.8 – 2.5 GHz / FSK and BPSK
Bit Rate (up/downlink) (AFSCN)	2 Kbps up / 1.024 Mbps down
Engagement Duration (Conop Profile)	3.9 minutes
Support Duration (Conop Profile)	9.8 minutes
Data Storage (Conop Profile)	Longest outage ~99 minutes
GPS Receivers (ACS)	Improved Ephemeris Accuracy
Processor Performance (ACS, Ephemeris)	Calculation Accuracy

C. TRADE STUDIES

As seen previously, due to the extent of the derived constraints, very few trade studies remain to be examined. These were system topology, component selection, and software.

1. Topology

Topology is the physical structure or architecture of the entire TT&C subsystem with respect to the processor. Three topologies are available to be used: Ring, Bus, and Star. A ring structure was automatically removed from the trade space, since any individual component failure would render the entire system unusable. Further analysis was required to determine which configuration was best between the bus and star topologies. This analysis included reliability, heritage, architecture complexity, and test equipment required. Table 11 summarizes the advantages and disadvantages between the bus and star topologies.

Table 11. Bus/Star Topology Comparison Summary

Advantages	
BUS	STAR
Facilitates addition of new nodes (components)	Highly reliable (failure in one interface effects no other interfaces)
Encourages use of standard protocols (1553)	Long heritage in space
Heritage with NASA (IMAGE, TAOS)	Very little protocol overhead
Traceable to 1553A/B Airborne systems bus, FDDI, and 1773 bus	Utilizes standard interfaces (RS 422, RS 232)
NASA heritage ensures standard test equipment should be available	Simple architecture
Most RAD hardened processors support 1553 bus structure	Standard interfaces make testing easier, and ensure test equipment is readily available
Disadvantages	
BUS	STAR
Slightly more complicated architecture	Large wiring harness required (more mass)
Limit to number of units on the bus (32)	Processor is single point of failure
While traceable to 1773, no space qualified 1773 interfaces are established	Cannot add nodes without affecting hub hardware and software

In determining which topology would be the best for this mission, several factors unique to the mission were considered. Since the project is not mass constrained, mass of wiring harness is not a factor. This mission requires high reliability and flexibility in operation since it is a demonstration unit. Heritage is a must, ensuring equipment is readily available and costs are minimized. After the final design is completed, additional nodes will not be required. The most significant advantages that a star topology provides over the bus concern software changes after launch and complexity in system design. From these considerations, it was fairly straightforward to choose the star topology (see Table 12).

Table 12. Bus/Star Comparison Conclusions

Topology	Significant Concerns
Both	Achieves a high reliability.
Both	Components readily available in industry.
Star	Longer heritage in space missions.
Star	Least complex system design.
Star	Require the least number of software changes after launch.

Selecting components was the next trade space to be completed. Once again, heritage was the primary consideration for the subsystem. Flight proven components would ensure the lowest degree of risk and reduce development costs, as well as technology costs. Table 13 summarizes the components chosen and their heritage.

2. Component Selection

a. Telemetry Data Unit

Typically this unit is a custom design which is produced by the system integrator. A custom design is often required because each satellite system has a unique implementation of equipment. Only the integrator and/or operator will know what equipment needs to be sampled and how often. This unit is sometimes referred to as the data acquisition system (DAS). If all the spacecraft equipment produces data, and the operator on the ground analyses this data, the DAS is the interim hardware that collects and formats the data for transmission to the operator or analysis by the onboard processor.

This is important because each spacecraft component only produces voltages or serial digital outputs.

Table 13. TT&C Subsystem Component Selection and Heritage

Component	Mass [Kg]	Power [W]	Heritage
Telemetry Data Unit	0.17	5.6	FLTSAT/ TRW, Hughes, Lockheed (custom design)
Conical Log Antenna	3.6	N/A	FLTSAT, INMARSAT/ Electrometrics
RAD 6000 Processor	11.8	10	IMAGE, SIRTF/ Lockheed-Martin
Data Storage Unit	5	6	ARGOS, Clementine/SEAKR
S Band Transponder	3	32	SOHO, Spot IV/V/Alcatel
TWTA	9.1	115	Hughes
GPS Receiver	4.2	20	GFO/3S Navigation, Ball Aerospace

In its basic configuration, the DAS consists of several multiplexers, some amount of memory, sample and hold circuitry, analog to digital converters (A/DC), formatting hardware, and a controller. Within the memory resides the sequencing for the sampling of each multiplexer line. The controller utilizes this sequence to poll each multiplexer line which sends the signal to a sample and hold circuit followed by the A/DC. Once in digital form, the data is converted to pulse coded modulation format (PCM) and either sent to the processor for health status analysis, a data storage device, or directly to the transponder for data downlink. Serial digital data may bypass the sample and hold circuit and A/DC hardware.

These units have become quite advanced in their implementation to date. Generally several data formats exist for a single spacecraft. This implies that the DAS is programmable, so that different sequences can be achieved to view different kinds of data. This programming of the sample sequence is manifested in different data formats. One format may include health data for the whole spacecraft while another may only dwell on payload specific data. In any event flexibility must be designed into the unit from the original spacecraft concept. Mithra will have four different formats, and several channels

will be available as spares. This requires that some degree of on orbit programming capability reside within the DAS.

b. Conical Log Antenna

To ensure the spacecraft will be able to receive commands from any attitude, it must have 4-pi steradian antenna availability [Ref. 1]. This can be achieved in many ways. The conical log antenna was selected because it has 2-pi steradian coverage in one antenna. Figure 24 summarizes the characteristics for one type of conical spiral antenna. Mithra employs one conical log antenna on the bottom of the transmit telescope pointed to nadir and one on the top of the receive telescope pointed to zenith providing the necessary 4-pi steradian coverage. Specifically, the conical log antenna from Electrometrics which operates between 1 and 10 GHz was selected [Ref. 8].

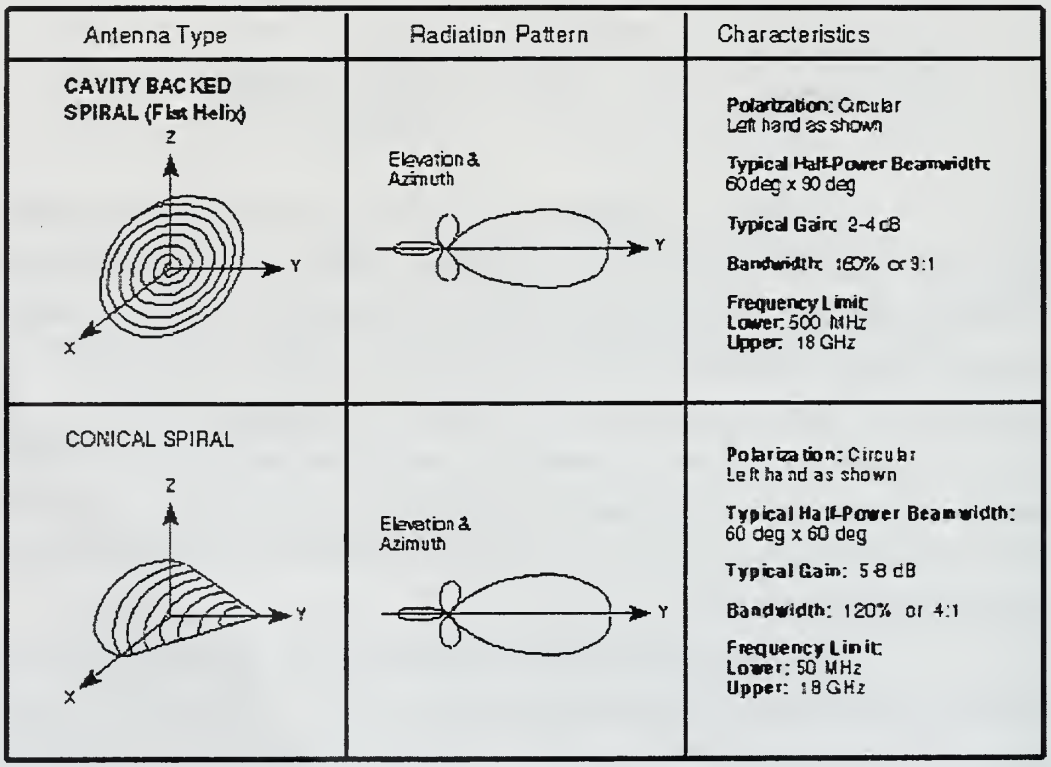

Figure 24. Conical Log Antenna Characteristics After Ref. [7]

c. RAD 6000 Processor

Since the ADCS required accuracy in pointing on the order of 10^{-3} the processor had to be capable of generating precision in its calculations to this degree. So for a single axis to have 360° on the order of 10^{-3} radians, we have 360000 degrees per radian per axis which is 55dB of dynamic range. Note that these will be floating point operations. To include cross products, multiply for 2 axes: 360000*360000 = $1.2968*10^{11}$ or 111dB of dynamic range. This is a rather large number. The most precise machine that is commercially available for space today is a 64 bit machine. This gives 2^{64-1} = $9.2*10^{18}$ or 189 dB of dynamic range. Certainly this meets the dynamic range requirements for precision, unfortunately 64 bit machines are very expensive since they are not typically used in space applications. Examining the next best processor leads to a 32 bit machine. Calculating its accuracy gives 2^{32-1} =$2.15*10^{9}$ or 93 dB of dynamic range. To determine the amount of dynamic range that is actually necessary requires that reverse engineering the crossproduct be completed. Looking at the requirement for the cross product: 111dB =$10*\text{Log}_{10}(2^{38-1})$, at least a 38 bit machine is required. Although this does not meet the requirements for the cross product precision, the machine can still be used if some intelligent use of the registers employed. That is to say, the accuracy required can be achieved if the registers are utilized effectively. For example, instead of calculating one cross product term in one clock cycle, calculate half of the value, the upper half, in one clock cycle, then calculate the lower half in the next clock cycle. The penalty is essentially in the speed of the calculation. Instead of performing the required calculation in one cycle, it is performed in two cycles. Allowing for margin, software may be effetively employed, again the creative use in the registers, to obtain 117 dB of dynamic range, or the equivalent of a 40 bit machine. Determining whether or not this action will hamper the ADCS system is the next step. There will be an effect if the speed of the processor is slow relative to the fastest attitude requirement. The fastest acting disturbance is the key, the gravity gradient torque for the Mithra spacecraft. For Mithra, the RAD 6000 processor is capable of 25 million instructions per second (MIPS) and is a 32 bit RISC machine with very good heritage in both the radiation hardened and non-radiation hardened versions. This turns out to be more than adequate for its ADCS calculations (and includes 100% margin). The RAD 6000 was essentially a commercial non-space processor first. The same design was then put through a radiation hardening fabrication process to create the rad hard version. Actually, it has been used in so many space applications that it is likely

that some software may actually have been already written, and could provide some cost savings in this respect upon implementation [Ref. 9].

d. Data Storage Unit

Typically spacecraft designers provide for a storage capability of telemetry data. This data may include general health data which is recorded when a spacecraft is not in view of a ground station. Such data may then be downloaded at the next available in view situation, typically called a 'support'. This storage may also be utilized while the payload is activated. In this respect, data is captured that is not being downloaded during real time, either because of ground station unavailability, or because the capacity of the data link will not support all the data being sampled. Data is then stored, perhaps compressed, then downloaded later on the smaller capacity link. Data storage requirements and analysis will be discussed later in this report. Mithra employs the SEAKR corporation 100 Mbyte data storage unit [Ref. 10].

e. S Band Transponder

Transferring the sampled and pulse code modulated telemetry data to the ground is the function of the transponder. This unit modulates the data onto a radio frequency (RF) carrier via a pre-selected format, typically called the waveform. Using the AFSCN determined the waveform for the Mithra mission: FSK uplink and BPSK downlink. Mithra will employ a transponder by Alcatel which supports uplink, downlink, and ranging functions compatible with the Space Ground Link System (SGLS) frequencies [Ref. 11]. Table 14 summarizes the performance specifications of this unit.

f. Travelling Wave Tube Amplifier

Ultimately, an RF source must drive the transponder. This may be in the form of an oven controlled oscillator, or an analog amplifier. Most spacecraft utilize the travelling wave tube amplifier to provide the RF for the communications equipment. Most communications spacecraft utilize these units, so Hughes was the primary vendor under consideration [Ref. 12]. A low power unit was selected to reduce power flux density on the ground to maintain international standard requirements. This value can be found in Appendix B, and will be discussed further in the link design section. Power draw for the unit is approximately 115 watts.

Table 14. S Band Transponder Characteristcs After Ref. [12]

Receiver	Transmitter
• S-Band (1025-2820 MHz) • Carrier Acquisition Threshold: -128 dBm • Input dynamic range: -128 to -50 dBm • Noise Figure: <5 dB (including diplexer) • Telecommand bit rate: up to 4 Kbps • Telecommand subcarrier: 8 or 16 Khz • Frequency stability: - initial setting: ± 5 ppm – global: ± 20 ppm *(initial setting + ageing + worst case in temperature)* • PM Demodulation losses <1 dB	• S-Band - Coherent mode: FTX = 240/221 FRX - Non coherent mode: FTX = FTX (2200-2300 MHz) • Frequency stability: as in receiver • Phase noise: < 3°rms (coherent) or 1°rms (non coherent) • Modulation index -TM 0.2 to 1.5 radpp -RG 0.5 to 1.5 radpp • RF Output Power: up to 37 dBm (even higher with external module)
Ranging	**General**
• Compatible with ESA two tone ESA MPTS and NASA STDN ranging systems • Ranging tones from 3 KHz to100 KHz or up to 1.5 MHz	• Mass: 3 Kg • Dimensions: 275 x 110 x 197 mm3 • Power consumption (power bus from 21 to 50 V): - Rx: 6 W - Tx: 26 W (PRF = 37 dBm)

g. GPS Receiver

In depth research found Alcatel, 3S Navigation and Ball Aerospace having units that support both C (clear) and P (precise) codes. Table 15 summarizes the performance for one such unit.

h. Software

Flight software and health maintenance software are both the least accurate estimates that are made at this early in the design. Very few algorithms exist for estimating software as a system. The only results that can be stated with any confidence are: spacecraft autonomy and payload control software are the major drivers for fast processors. Mithra will require a significant amount of payload control as well as a certain degree of autonomy classifying it as a very complex spacecraft [Ref. 1]. One algorithm

does provide a means to calculate an estimate for health maintenance software [Ref. 1]. Research from the Aerospace Corporation recommended scaling subsystem specific software based on complexity with similar programs if possible. A complete description of the calculation for software size is in the appendix of this report. Table 16 summarizes the results for the software size estimate for Mithra.

Table 15. GPS Receiver Characteristics After Ref. [13]

Position and Velocity Accuracy		**Dimensions**	
SPS Position	220 m SEP	**Dual RPU**	74 mm x 275 mm x 170 mm
Filtered Position	100 m SEP	**Quad Preamplifier**	51 mm x 138 mm x 76 mm
Filtered Velocity	0.5 m/sec RMS	**Antenna**	73 mm x 73 mm x 5.7 mm
Attitude Accuracy		**General**	
Roll	0.5 degree RMS	**Radiation:**	100 KRad SI
Roll Rate	1.0 degree/sec RMS	**EMI/EMC:**	MIL-STD-461C, Class A1a
Pitch	0.5 degree RMS	**Reliability:**	Ps= 0.95 single , Ps= 0.99rednd nt
Pitch Rate	1.0 degree/sec RMS	**Shock:**	40g, 11 msec pulse
Yaw	0.5 degree RMS	**Pressure:**	< $1x10^{-6}$ torr
Yaw Rate	1.0 degree/sec RMS	**Host Interface:**	Dual, full Duplex EIA RS-422
Environmental		**Weight**	
Operating Temperature:	-20 to +60 degree C	**Dual RPU**	3.6 Kg
Storage Temperature:	-70 to + 65 degree C	**Quad Preamplifier**	0.5 Kg
Time-To-First-Fix:		**Antenna (each)**	0.1 Kg
Cold Start	<30 minutes after power-on		
Warm Start	<3 minutes after power-on		

Orbit Determination Accuracy	
Semi-Major Axis	90 m RMS
Eccentricity	$5x10^{-6}$ radians RMS
Inclination	$5x10^{-6}$ radians RMS
Right Ascension of Ascending Node	$5x10^{-6}$ radians RMS
Argument of Perigee	0.01 radians RMS
Sum of True Anomaly and Argument of Perigee	$2x10^{-3}$ radians RMS

Power	
Operating Power	14-23 V dc (18 V dc Nominal) OR 24-32 V dc (28 V dc Nominal)
Power Consumption	20 Watt

3. Link Design

AFSCN requirements, altitude, and transponder characteristics drive much of the link design. Modulation and demodulation requirements were previously discussed (FSK and BPSK). For a recommended Bit Error Rate (BER) of $1*10^{-5}$, we can determine the

required Eb/No (energy in a bit per thermal noise). Figure 25 summarizes the required Eb/No for both FSK and BPSK. Worst case limb of the earth range was used for the path loss in the detailed link design as well as losses including filter roll off, atmospheric rain

Table 16. Software Size Estimate Summary

Software Type	Lines of Code
Health Maintenance	43,000
Subsystem Specific	1,200,000
Total	1,243,000

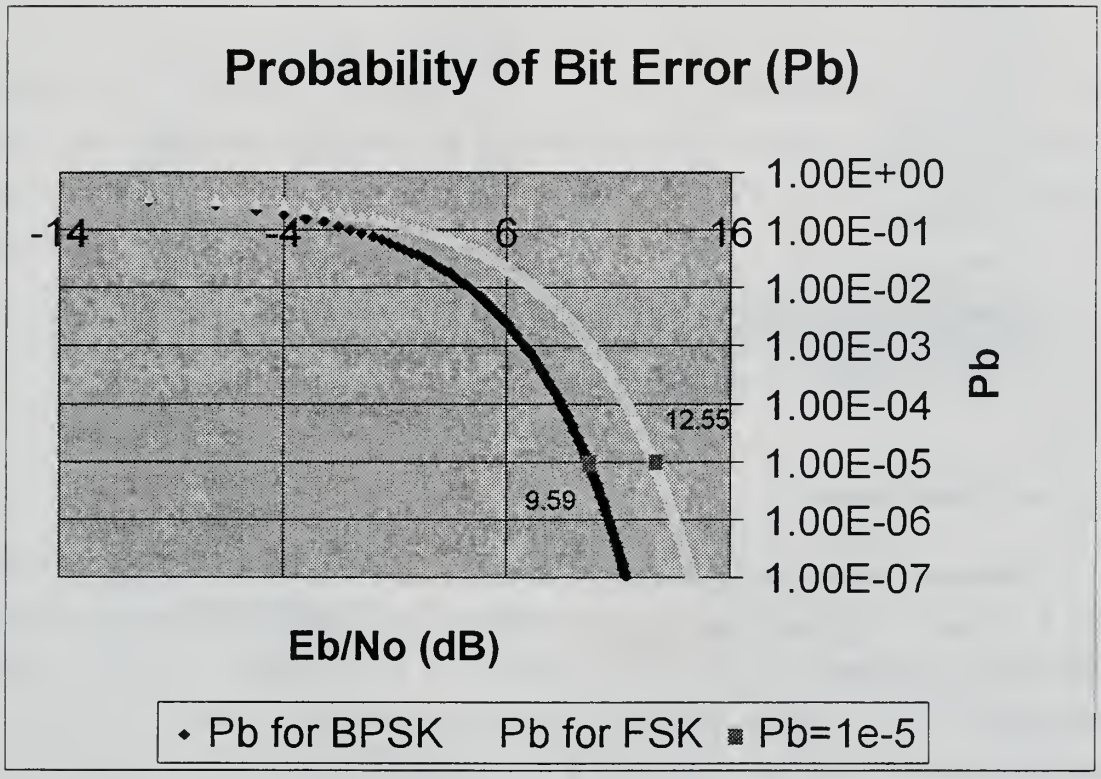

Figure 25. Theoretical Probability of Bit Error (Pb)

loss and polarization loss. A detailed analysis of the link design for uplink and all three downlink carriers appears in Appendix B. Table 17 summarizes the link design denoting link margin as the performance specification. As is evident from the analysis, a large degree of margin is found in the uplink (2 Kbps). This is a result of the combination of low altitude and large ground antenna gain (calculated using the smallest AFSCN antenna

of 10 meter diameter, all ARTS sites have 10 and 18 meter diameter antennas). Thus it is likely that the spacecraft will receive a command from any attitude given that it has 4-pi steradian coverage via the conical log antennas. Also of note is the largest data rate link (1.024 Mbps). As expected it has the least amount of margin, but it meets and exceeds the requirements. At this worst case range we are also likely to be able to receive all data when the data storage unit is in the dump mode. The main point of this analysis is to show that the link design is conservative, and meets all requirements.

Table 17. MITHRA Link Design Summary

Link	1.024 Mbps	256 Kbps	128 Kbps	2 Kbps
EIRP	-5.6	-5.6	-5.6	78
G/T	26.6	26.6	26.6	-22.7
Bit Rate	-60	-54	-51	-33
Eb/No Rqrd	-9.5	-9.5	-9.5	-12.5
Path Loss	-169.5	-169.5	-169.5	-167.5
Other Loss	-3.25	-3.25	-3.25	-4.75
Boltzmann	228.6	228.6	228.6	228.6
Total Margin	**7.3 dB**	**13.3 dB**	**16.3 dB**	**66.1 dB**

4. Data Storage

Telemetry storage estimation is probably the most difficult calculation to perform. This is because unless each spacecraft component has detailed data specifications and performance requirements, very little capacity can be calculated. In other words, everything would be a guess, and a very low fidelity estimate. Fortunately, similar data could be found for another mission which is very similar to this design [Ref. 14]. The Relay Mirror Experiment (RME) was a monocle relay mirror which utilized a single telescope to perform the same mission Mithra is to be designed for. It was also a demonstration vehicle, and is considered the precursor to the Bifocal Relay Mirror Experiment (Mithra). With such similarities, its telemetry list and data sampling requirements would provide a very high fidelity estimate as long as it was scaled appropriately. Scaling and tailoring included removing telemetry items for components that were not used in Mithra, as well as adding components that were used in Mithra. For

example, RME utilized a single momentum wheel for gyroscopic stability in its ADCS. Mithra on the other hand uses four reaction wheels in a pyramidal scheme. Thus the momentum wheel telemetry channel was replaced with telemetry and associated sampling for the reaction wheels. Additionally, doubling the payload telemetry (since Mithra employs two telescopes vs. one) was in order. This analysis revealed much about the operation of Mithra. Included are focal plane arrays for ground targeting as well as jitter measurement, and payload thermal data. A detailed description of the Mithra telemetry list (over 900 telemetry channels) that includes sample rates and type of data (Bilevel, Analog, Serial, or Digital) is included as Appendix D. From this list, four data formats were derived to include 1) Health data, 2) Payload Only data, 3) Selected Payload and ACS data, 4) ACS data and EPS data. Different data formats provided flexibility in the operation of the Mithra spacecraft and payload. Not only could a significant amount of health data be stored and forwarded, but all payload generated data could be recorded during an engagement if required. A significant number of spare telemetry channels are also accounted for within the telemetry lists (5 Serial, 6 Bilevel, 24 Analog). Table 18 summarizes the Mithra telemetry list.

Table 18. MITHRA Telemetry List Summary

Parameter Name	Value
Analog/Bilevel	43% (423)
Serial/Digital	57% (484)
Telemetry Channels	900+
Total Storage	100 Mbytes (50% margin)
Format 1	8 hours Health data
Format 2	4 minutes Payload only
Format 3	10 minutes selected Payload /ACS
Format 4	19 hours ACS & EPS
Download time for 62.5 Mbytes	8.1 minutes

D. FINAL DESIGN

A block diagram of the system gives a final and comprehensive description of the TT&C subsystem. Figure 26 presents the block diagram. So for a summary of the main system points, the subsystem is in a star configuration which has full component

redundancy to yield the highest reliability. A margin of 7dB for the weakest link allows connectivity to the ground for downlink and a margin of 66dB for the uplink. There is 4-pi steradian coverage using two conical log antennas to ensure commanding capability for any attitude. Data storage capacity has a margin of almost 50% by choosing the SEAKR 100 Mbyte solid state recorder. This is a high fidelity estimate which includes margin since only 62.5 Mbytes is necessary to perform all planned requirements. The processor is capable of 25 MIPS which also includes 100% margin, and 1.24 million lines of code are estimated for the spacecraft onboard software.

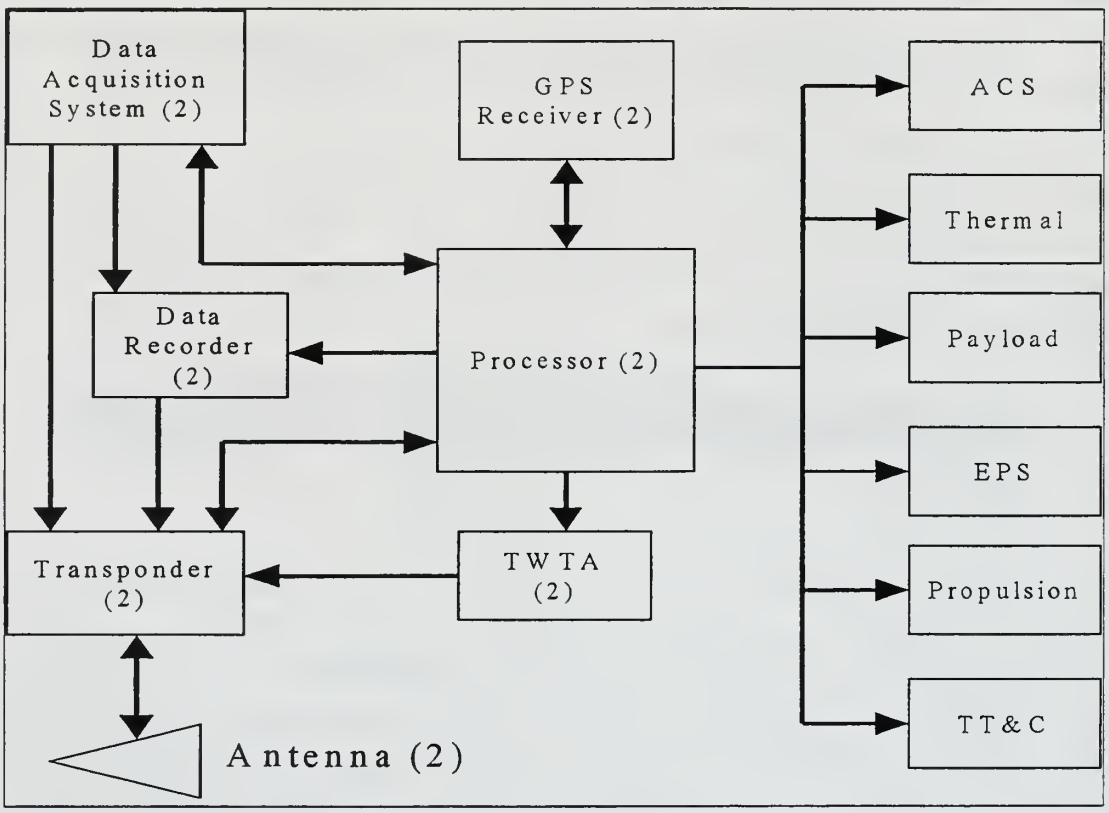

Figure 26. Mithra Final Design Block Diagram

APPENDIX A. SPACECRAFT TT&C COMPONENT LIST

These are included as documentation for the Mithra spacecraft design.

Spacecraft Component List						
Task	Qty	Length [cm]	Width [cm]	Height [cm]	Mass [Kg]	Power [W]
Data Acquisition System						
MMP-900b	2	3.81	3.81	5.08	0.17	5.6
includes PCM encoder						
TT&C Transponder	2	27.5	11	19.7	3	32
includes Diplexer						
includes Filter						
TT&C Antenna	2	38.1	12.7	12.7	3.6	
Command Processor	2	28.6	20.3	7.6	1	10
Recorder Unit (1 Gbit)	2	9.5	14.2	16.8	5	6
GPS Receiver	2	7.4	27.5	17	4.2	20
TWTA	2	48	49	8	9.1	115
TT&C system power						377.2
TT&C system mass					52.14	
	Max Temp [C]	Min Temp [C]	Op Temp Range [C]	Heritage		
Data Acquisition System						
MMP-900b	44	-22	8 to 17			
includes PCM encoder						
TT&C Transponder	57	-20	3 to 10	SOHO, Spot IV/V, Telecom 2		
includes Diplexer						
includes Filter						
TT&C Antenna				FLTSAT, INMARSAT		
Command Processor	65	-25	3 to 20	IMAGE, SIRTF		

Spacecraft Component List						
TT&C Coax						
Recorder Unit (1 Gbit)	60	-25	3 to 20	ARGOS, Clementine, Mars Global Surveyor		
GPS Receiver	60	-20	3 to 20	GFO		
TWTA	45	-15	3 to 7	Hughes		

APPENDIX B. SPACECRAFT DETAILED LINK DESIGN

This appendix contains data and calculations that were used to determine the link design for the Mithra spacecraft TT&C subsystem design. These are provided as documentation.

Spacecraft Detailed Link Design					
	Ground Uplink	Carrier 2	Carrier 1	Carrier 1	
Grnd transmitter (Xtr) frequency (freq) [Hz]	1.84E+09	2.2975E+09	2.2935E+09	2.2942E+09	S/C Xtr freq [Hz]
Grnd Xtr power [W]	2800	1	1	1	S/C Xtr power [W]
Grnd antenna (Ant) diameter [m]	10	0.1	0.1	0.1	S/C Ant diameter [m]
Grnd antenna pointing error [deg]	0.1	1	1	1	S/C Ant pointing error [deg]
Grnd ant feed transmit efficiency [%]	75	55	55	55	S/C ant feed transmit efficiency [%]
Grnd ant feed receive (rcv) efficiency [%]	75	55	55	55	S/C ant feed rcv efficiency [%]
Grnd receiver noise temp [K]	95	150	150	150	S/C receiver noise temp [K]
Grnd receiver bandwidth (BW) [Mhz]	0.002	1.024	0.256	0.128	S/C receiver BW [Mhz]
Bit Rate[b/s]	2.00E+03	1024000	256000	128000	
	UPLINK	DOWNLINK	DOWNLINK	DOWNLINK	
Frequency [Ghz]	1.8398E+09	2.2975E+09	2.2935E+09	2.2942E+09	
wavelength[m]	0.1631	0.1306	0.1308	0.1308	
Grnd ant beam width (qb) [deg]	1.141	350.000	350.000	350.000	S/C ant beamwidth(qb) [deg]
Grnd Xtr power [dB]	34.472	0.000	0.000	0.000	S/C Xtr power [dB]
Grnd ant feed loss [dB]	-1.249	-2.596	-2.596	-2.596	S/C ant feed loss [dB]
Grnd antenna gain [dB]	45.696	-3.000	-3.000	-3.000	S/C ant gain [dB]
Grnd EIRP [dB]	78.918	-5.596	-5.596	-5.596	S/C EIRP [dB]
Grnd ant pointing error loss [dB]	-1.402	-0.049	-0.049	-0.049	S/C ant pointing error loss [dB]
path loss [dB]	-167.574	-169.504	-169.489	-169.489	path loss [dB]
atmospheric/rain loss [dB]	-2.500	-1.000	-1.000	-1.000	atmospheric/rain loss [dB]

Spacecraft Detailed Link Design					
polarization loss [dB]	-0.250	-0.250	-0.250	-0.250	polarization loss [dB]
Filter Roll Off [dB]	-3.000	-2.000	-2.000	-2.000	Filter Roll Off [dB]
S/C antenna beam width (qb) [deg]	350.000	0.720	0.721	0.721	Grnd antenna beam width (qb) [deg]
S/C feed loss [dB]	-2.596	-1.249	-2.596	-2.596	Grnd feed loss [dB]
S/C antenna gain [dB]	-1.000	47.626	47.611	47.611	Grnd ant gain [dB]
S/C antenna pointing error [dB]	-0.049	-2.129	-2.126	-2.126	Grnd antenna pointing error [dB]
S/C received (Rcvd) /carrier power [dB]	-99.454	-134.153	-135.497	-135.497	Grnd Rcvd /carrier power [dB]
S/C noise power density [dBK]	-206.840	-208.824	-208.824	-208.824	Grnd noise power density [dBK]
S/C receiver bandwidth [dB]	60.103	33.010	33.010	33.010	Grnd receiver BW [dB]
S/C receiver noise power [dB]	-146.737	-175.814	-175.814	-175.814	Grnd receiver noise power [dB]
		-146.426	-146.426	-146.426	Grnd PFD [dB]
		-182.446	-182.446	-182.446	Grnd PFD/4Khz [dB limited to approx -148dB]
Required (Rqrd) Eb/No	12.577	9.590	9.590	9.590	Rqrd Eb/No
S/C rcvd carrier to noise ratio [dB]	47.28286	41.661	40.317	40.317	Grnd rcvd carrier to noise ratio [dB]
S/C rcvd Eb/No[dB]	74.38	14.57	19.24	22.26	Grnd rcvd Eb/No [dB]
Margin [dB]	65.85	6.48	12.51	15.52	
r [km]	3103.555	300000000	c [m/sec]		
k [J/K]	1.38E-23				
Eb/No required for Pb = 1e-5	9.590	Downlink (BPSK)			
Eb/No required for Pb = 1e-5	12.577	Uplink (FSK)			
40.60892091	system C/N ratio [dB]				
91.40369579	S/C antenna beamwidth(qb) [deg]				

APPENDIX C. DATA STORAGE CALCULATION

This appendix contains data and calculations for the data storage requirement for the Mithra spacecraft TT&C subsystem desgin. These are provided as documentation.

Data Storage Requirement				
Type of data	Payload & ACS	Health	Payload only	ACS & EPS
Format #	1	2	3	4
Data rate for the format [bps]	758751.952	17326.952	2069943.750	7206.250
Total Storage [bits]	5.00E+08	5.00E+08	5.00E+08	5.00E+08
Duration of time stored [sec]	658.977	28856.778	241.552	69384.215
Duration of time stored [min]	10.983	480.946	4.026	1156.404
Duration of time stored [hrs]	0.183	8.016	0.067	19.273

Time to download Calculation:	
Amount of stored data [bits]	5.0E+08
using carrier1 data link [bits/sec]	1.024E+06
Time for download [sec]	488.2813
Time for download [min]	8.138
Avg support duration: 9.8 minutes	
Avg engagement time: 3.9 minutes	
Total Storage Required [bytes]	6.25E+07

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APPENDIX D. SPACECRAFT TELEMETRY LIST

This appendix contains data and calculations used in the TT&C subsystem design for the Mithra spacecraft. Serial/Digital and Analog/Bilevel measurements are included. These are included as documentation.

ID	Analog/Bilevel Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
1	XMT RM Pitch Position	50	12	Payload	600	600		600	
2	XMT RM Yaw Position	50	12	Payload	600	600		600	
3	RCV RM Pitch Position	50	12	Payload	600	600		600	
4	RCV RM Yaw Position	50	12	Payload	600	600		600	
5	XMT FSM Pitch Position	100	12	Payload	1200	1200		1200	
6	XMT FSM Yaw Position	100	12	Payload	1200	1200		1200	
7	RCV FSM Pitch Position	100	12	Payload	1200	1200		1200	
8	RCV FSM Yaw Position	100	12	Payload	1200	1200		1200	
9	XMT OM Pitch Position	2000	12	Payload	24000	24000		24000	
10	XMT OM Yaw Position	2000	12	Payload	24000	24000		24000	
11	RCV OM Pitch Position	2000	12	Payload	24000	24000		24000	
12	RCV OM Yaw Position	2000	12	Payload	24000	24000		24000	
13	CAS Target Beacon x position	100	12	Payload	1200	1200		1200	
14	CAS Target Beacon y position	100	12	Payload	1200	1200		1200	
15	CAS Source Beacon X position	100	12	Payload	1200	1200		1200	
16	CAS Source Beacon Y position	100	12	Payload	1200	1200		1200	
17	Relay Beam Intensity 1	100	8	Payload	800	800		800	
18	Relay Beam Intensity 2	100	8	Payload	800	800		800	
19	Relay Beam Intensity	100	8	Payload	800	800		800	

ID	Analog/Bilevel Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
	3								
20	Relay Beam Intensity 4	100	8	Payload	800	800		800	
21	Source Pitch Error (Quad Cell)	2000	12	Payload	24000	24000		24000	
22	Source Yaw Error (Quad Cell)	2000	12	Payload	24000	24000		24000	
23	Source Intensity	1000	8	Payload	8000	8000		8000	
24	Source Beacon Present	6.25	2	Payload	12.5	12.5		12.5	
25	Target Pitch Error (Quad Cell)	2000	12	Payload	24000	24000		24000	
26	Target Yaw Error (Quad Cell)	2000	12	Payload	24000	24000		24000	
27	Target Intensity	1000	8	Payload	8000	8000		8000	
28	Target Beacon Present	6.25	2	Payload	12.5	12.5		12.5	
29	CP1 Engineering Data	-	S/D	Payload				0	
30	CP1 Table Dump	-	S/D	Payload				0	
31	CAS Data	-	S/D	Payload				0	
32	Payload Servo Actuator On/Off	6.25	2	Payload	12.5	12.5		12.5	
33	Payload CEA On/Off	6.25	2	Payload	12.5	12.5		12.5	
34	Payload Thermal Subsystem On/Off	6.25	2	Payload	12.5	12.5		12.5	
35	Payload Caging Mechanism On/Off	6.25	2	Payload	12.5	12.5		12.5	
36	Payload RM Thermal Subsystem On/Off	6.25	2	Payload	12.5	12.5	12.5	12.5	
37	XMT RM Pitch Monitor 1	6.25	8	Payload	50	50		50	
38	XMT RM Pitch Monitor 2	6.25	8	Payload	50	50		50	
39	XMT RM Yaw Monitor 1	6.25	8	Payload	50	50		50	
40	XMT RM Yaw Monitor 2	6.25	8	Payload	50	50		50	
41	RCV RM Pitch Monitor 1	6.25	8	Payload	50	50		50	
42	RCV RM Pitch Monitor 2	6.25	8	Payload	50	50		50	
43	RCV RM Yaw Monitor 1	6.25	8	Payload	50	50		50	
44	RCV RM Yaw Monitor 2	6.25	8	Payload	50	50		50	

ID	Analog/Bilevel Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
45	RCV FSM/OM Monitor 1	6.25	8	Payload	50	50		50	
46	XMT FSM/OM Monitor 2	6.25	8	Payload	50	50		50	
47	RCV FSM/OM Monitor 1	6.25	8	Payload	50	50		50	
48	RCV FSM/OM Monitor 2	6.25	8	Payload	50	50		50	
49	CEA Monitor 1	6.25	8	Payload	50	50		50	
50	CEA Monitor 2	6.25	8	Payload	50	50		50	
51	CEA Monitor 3	6.25	8	Payload	50	50		50	
52	CEA Monitor 4	6.25	8	Payload	50	50		50	
53	CEA Monitor 5	6.25	8	Payload	50	50		50	
54	Temp Zone 1	6.25	8	Payload	50	50		50	
55	Temp Zone 2	6.25	8	Payload	50	50		50	
56	Temp Zone 3	6.25	8	Payload	50	50		50	
57	Temp Zone 4	6.25	8	Payload	50	50		50	
58	Temp Zone 5	6.25	8	Payload	50	50		50	
59	Temp Zone 6	6.25	8	Payload	50	50		50	
60	XMT FPS 1 Temperature	6.25	8	Payload	50	50		50	
61	XMT FPS 2 Temperature	6.25	8	Payload	50	50		50	
62	XMT FSM Temperature	6.25	8	Payload	50	50		50	
63	RCV FPS 1 Temperature	6.25	8	Payload	50	50		50	
64	RCV FPS 2 Temperature	6.25	8	Payload	50	50		50	
65	RCV FSM Temperature	6.25	8	Payload	50	50		50	
66	CAS Temperature	6.25	8	Payload	50	50		50	
67	XMT RM Support Plate 1 Temperature	6.25	8	Payload	50	50		50	
68	XMT RM Support Plate 2 Temperature	6.25	8	Payload	50	50		50	
69	RCV RM Support Plate 1 Temperature	6.25	8	Payload	50	50		50	
70	RCV RM Support Plate 2 Temperature	6.25	8	Payload	50	50		50	
71	CEA Temperature	6.25	8	Payload	50	50		50	
72	XMT Optics Bench 1 Temperature	6.25	8	Payload	50	50		50	
73	XMT Optics Bench 2 Temperature	6.25	8	Payload	50	50		50	
74	XMT Optics Bench 3	6.25	8	Payload	50	50		50	

ID	Analog/Bilevel Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
	Temperature								
75	RCV Optics Bench 1 Temperature	6.25	8	Payload	50	50		50	
76	RCV Optics Bench 2 Temperature	6.25	8	Payload	50	50		50	
77	RCV Optics Bench 3 Temperature	6.25	8	Payload	50	50		50	
78	RM Heater Control Electronics Temperature	6.25	8	Payload	50	50		50	
79	RCV RM Temperature	6.25	8	Payload	50	50	50	50	
80	XMT RM Temperature	6.25	8	Payload	50	50	50	50	
81	Zone 1 power monitor	6.25	2	Payload	12.5	12.5		12.5	
82	Zone 2 power monitor	6.25	2	Payload	12.5	12.5		12.5	
83	Zone 3 power monitor	6.25	2	Payload	12.5	12.5		12.5	
84	Zone 4 power monitor	6.25	2	Payload	12.5	12.5		12.5	
85	Zone 5 power monitor	6.25	2	Payload	12.5	12.5		12.5	
86	Zone 6 power monitor	6.25	2	Payload	12.5	12.5		12.5	
87	XMT RM Pitch Actuator Current	6.25	8	Payload	50	50		50	
88	XMT RM Yaw Actuator Current	6.25	8	Payload	50	50		50	
89	XMT FSM Pitch Actuator Current (push)	6.25	8	Payload	50	50		50	
90	XMT FSM Pitch Actuator Current (pull)	6.25	8	Payload	50	50		50	
91	XMT FSM Yaw Actuator Current (push)	6.25	8	Payload	50	50		50	
92	XMT FSM Yaw Actuator Current (pull)	6.25	8	Payload	50	50		50	
93	XMT RM Inner Heater Current	6.25	8	Payload	50	50		50	
94	XMT RM Outer Heater Current	6.25	8	Payload	50	50		50	

ID	Analog/Bilevel Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
95	RCV RM Pitch Actuator Current	6.25	8	Payload	50	50		50	
96	RCV RM Yaw Actuator Current	6.25	8	Payload	50	50		50	
97	RCV FSM Pitch Actuator Current (push)	6.25	8	Payload	50	50		50	
98	RCV FSM Pitch Actuator Current (pull)	6.25	8	Payload	50	50		50	
99	RCV FSM Yaw Actuator Current (push)	6.25	8	Payload	50	50		50	
100	RCV FSM Yaw Actuator Current (pull)	6.25	8	Payload	50	50		50	
101	RCV RM Inner Heater Current	6.25	8	Payload	50	50	50	50	
102	RCV RM Outer Heater Current	6.25	8	Payload	50	50	50	50	
103	Minor Frame Counter	100	8	TT&C	800	800	800		
104	Command Accept Counter	6.25	8S/D	TT&C			0		
105	Command Reject Register	6.25	8S/D	TT&C			0		
106	Command Time of Day Clock	6.25	16S/D	TT&C			0		
107	Command Replica (LEC)	6.25	48S/D	TT&C			0		
108	Spacecraft PB-3 Clock	6.25	48S/D	TT&C			0		
109	TSS Enable Status	6.25	2	TT&C	12.5	12.5	12.5		
110	CP1 Correlation Register	6.25	40S/D	TT&C			0		
111	CP2 Correlation Register	6.25	40S/D	TT&C			0		
112	CP1/CP2 Correlation Register Status	6.25	2	TT&C	12.5	12.5	12.5		
113	Ground Corr (S-Pulse) Time Register	6.25	48S/D	TT&C			0		
114	Ground Corr (S-Pulse) Enable Status	6.25	2	TT&C	12.5	12.5	12.5		
115	CSM Dump	6.25	S8	TT&C			0		
116	CSM Disable Mode	6.25	2	TT&C	12.5	12.5	12.5		
117	CSM Load Mode	6.25	2	TT&C	12.5	12.5	12.5		

ID	Analog/Bilevel Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hilth)	Format 3 (Payload)	Format 4 (ACS & EPS)
118	CSM Enable Mode	6.25	2	TT&C	12.5	12.5	12.5		
119	CSM Dump Mode	6.25	2	TT&C	12.5	12.5	12.5		
120	CSM Overall Status	6.25	2	TT&C	12.5	12.5	12.5		
121	DTU On/Off	6.25	2	TT&C	12.5	12.5	12.5		
122	DTU Format	6.25	2	TT&C	12.5	12.5	12.5		
123	DSU 1 Memory Address	6.25	16S/D	TT&C			0		
124	DSU 2 Memory Address	6.25	16S/D	TT&C			0		
125	DSU 1 Operating Mode	6.25	2	TT&C	12.5	12.5	12.5		
126	DSU 2 Operating Mode	6.25	2	TT&C	12.5	12.5	12.5		
127	DSU 1 Power	6.25	2	TT&C	12.5		12.5		
128	DSU 2 Power	6.25	2	TT&C	12.5		12.5		
129	DSU 1 Temperature	6.25	8	TT&C	50		50		
130	DSU 2 Temperature	6.25	8	TT&C	50		50		
131	PB-3 Clock Module Temperature	6.25	8	TT&C	50	50	50		
132	DTU Temperature	6.25	8	TT&C	50	50	50		
133	CDU Temperature	6.25	8	TT&C	50	50	50		
134	Test Serial digital	6.25		TT&C	0	0	0		
135	Test Bilevel	6.25	2	TT&C	12.5	12.5	12.5		
136	Test Single Ended Analog	6.25	8	TT&C	50	50	50		
137	Test Differential Analog	6.25	8	TT&C	50	50	50		
138	Watchdog Timer Time Count	6.25	16S/D	TT&C			0		
139	Watchdog Timer Output ENBL/DSBL	6.25	2	TT&C	12.5	12.5	12.5		
140	Encryptor E1A On/Off	6.25	2	TT&C	12.5	12.5	12.5		
141	Encryptor E1B On/Off	6.25	2	TT&C	12.5	12.5	12.5		
142	Encryptor E2 On/Off	6.25	2	TT&C	12.5	12.5	12.5		
143	Xpndr 1 Xmtr Power output	6.25	8	TT&C	50	50	50		
144	Xpndr 1 Xmtr Temperature	6.25	8	TT&C	50	50	50		
145	Xpndr 1 Rcvr Signal Presence	6.25	2	TT&C	12.5	12.5	12.5		
146	Xpndr 1 Rcvr Signal Strength	6.25	8	TT&C	50	50	50		
147	Xpndr 1 Rcvr Temperature	6.25	8	TT&C	50	50	50		

ID	Analog/Bilevel Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
148	Xpndr 1 Ranging On/Off	6.25	2	TT&C	12.5	12.5	12.5		
149	Xpndr 1 Coherent/Non-Coherent	6.25	2	TT&C	12.5	12.5	12.5		
150	Xpndr 1 Downlink TLM On/Off	6.25	2	TT&C	12.5	12.5	12.5		
151	Xpndr 1 Rcvr Decoder Active	6.25	2	TT&C	12.5	12.5	12.5		
152	RF String 1A Status	6.25	2	TT&C	12.5	12.5	12.5		
153	RF String 1B Status	6.25	2	TT&C	12.5	12.5	12.5		
154	Xpndr 2 Xmtr Power output	6.25	8	TT&C	50	50	50		
155	Xpndr 2 Xmtr Temperature	6.25	8	TT&C	50	50	50		
156	Xpndr 2 Rcvr Signal Presence	6.25	2	TT&C	12.5	12.5	12.5		
157	Xpndr 2 Rcvr Signal Strength	6.25	8	TT&C	50	50	50		
158	Xpndr 2 Rcvr Temperature	6.25	8	TT&C	50	50	50		
159	Xpndr 2 Ranging On/Off	6.25	2	TT&C	12.5	12.5	12.5		
160	Xpndr 2 Coherent/Non-Coherent	6.25	2	TT&C	12.5	12.5	12.5		
161	Xpndr 2 Downlink TLM On/Off	6.25	2	TT&C	12.5	12.5	12.5		
162	Xpndr 2 Rcvr Decoder Active	6.25	2	TT&C	12.5	12.5	12.5		
163	Carrier 1 Xmtr 1 On/Off	6.25	2	TT&C	12.5	12.5	12.5		
164	Carrier 1 Xmtr 2 On/Off	6.25	2	TT&C	12.5	12.5	12.5		
165	Carrier 1 Xmtr Select Status	6.25	2	TT&C	12.5	12.5	12.5		
166	Carrier 2 Xmtr Bus On/Off	6.25	2	TT&C	12.5	12.5	12.5		
167	TDU Carrier 2 Xmtr On/Off Status	6.25	2	TT&C	12.5	12.5	12.5		
168	Carrier 2 Status	6.25	2	TT&C	12.5	12.5	12.5		
169	Carrier 2 Xmtr Power Output	6.25	8	TT&C	50	50	50		
170	Carrier 2 Xmtr Temperature	6.25	8	TT&C	50	50	50		
171	RF String 2 Status	6.25	2	TT&C	12.5	12.5	12.5		

ID	Analog/Bilevel Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
172	Freq Std Inner Oven Power	6.25	8	TT&C	50	50	50		
173	Freq Std Outer Oven Power	6.25	8	TT&C	50	50	50		
174	Freq Std RF Signal Level	6.25	8	TT&C	50	50	50		
175	Freq Std 28v Monitor	0.244	8	TT&C	1.952	1.952	1.952		
176	Freq Std Relay Status 1	6.25	2	TT&C	12.5		12.5		
177	Freq Std Relay Status 2	6.25	2	TT&C	12.5		12.5		
178	Freq Std Relay Status 3	6.25	2	TT&C	12.5		12.5		
179	Freq Std Relay Status 4	6.25	2	TT&C	12.5	12.5	12.5		
180	Freq Std Relay Status 5	6.25	2	TT&C	12.5	12.5	12.5		
181	Freq Std Relay Status 6	6.25	2	TT&C	12.5	12.5	12.5		
182	Freq Std Relay Status 7	6.25	2	TT&C	12.5	12.5	12.5		
183	Freq Std Relay Status 8	6.25	2	TT&C	12.5	12.5	12.5		
184	Freq Std Relay Status 9	6.25	2	TT&C	12.5	12.5	12.5		
185	Freq Std Relay Status 10	6.25	2	TT&C	12.5	12.5	12.5		
186	Freq Std Relay Status 11	6.25	2	TT&C	12.5	12.5	12.5		
187	Freq Std Relay Status 12	6.25	2	TT&C	12.5	12.5	12.5		
188	Freq Std Status	6.25	2	TT&C	12.5	12.5	12.5		
189	Nadir Carrier 1 Antenna Temperature	6.25	8	TT&C	50	50	50		
190	Nadir Carrier 2 Antenna Temperature	6.25	8	TT&C	50	50	50		
191	Zenith Antenna Temperature	6.25	8	TT&C	50	50	50		
192	D1 Uplink Hardline/RF(R1/R2)	6.25	2	TT&C	12.5	12.5	12.5		
193	Selected Uplink Path (1/2)	6.25	2	TT&C	12.5	12.5	12.5		
194	Authenticator 1 Enable Status	6.25	2	TT&C	12.5	12.5	12.5		

ID	Analog/Bilevel Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
195	Authenticator 2 Enable Status	6.25	2	TT&C	12.5	12.5	12.5		
196	Authenticator 1 Count	6.25	32S/D	TT&C			0		
197	Authenticator 2 Count	6.25	32S/D	TT&C			0		
198	TDU Power Supply 1 On/Off	6.25	2	TT&C	12.5	12.5	12.5		
199	TDU Power Supply 2 On/Off	6.25	2	TT&C	12.5	12.5	12.5		
200	TDU Power Supply +5V	6.25	8	TT&C	50	50	50		
201	TDU Power Supply +12V	6.25	8	TT&C	50	50	50		
202	TDU Power Supply -12V	6.25	8	TT&C	50	50	50		
203	TDU Essential Bus +5V	6.25	8	TT&C	50	50	50		
204	TDU Essential Bus +5V	6.25	8	TT&C	50	50	50		
205	TDU Supply 1 Temperature	6.25	8	TT&C	50	50	50		
206	TDU Supply 2 Temperature	6.25	8	TT&C	50	50	50		
207	TDU Cal Monitor 1 (0.1V)	6.25	8	TT&C	50	50	50		
208	TDU Cal Monitor 2 (+2.5V)	6.25	8	TT&C	50	50	50		
209	TDU Cal Monitor 3 (+5.0V)	6.25	8	TT&C	50	50	50		
210	CP2 Engineering Data			ACS	0	0	0		0
211	CP2 Table Dumps			ACS	0	0	0		0
212	Star Tracker 1 Power	6.25	2	ACS	12.5	12.5	12.5		12.5
213	Star Tracker 1 Power	6.25	2	ACS	12.5	12.5	12.5		12.5
214	Coarse Sun Sensor 1 Power	6.25	2	ACS	12.5	12.5	12.5		12.5
215	Coarse Sun Sensor 2 Power	6.25	2	ACS	12.5	12.5	12.5		12.5
216	Coarse Sun Sensor 3 Power	6.25	2	ACS	12.5	12.5	12.5		12.5
217	Gyro 1 Power	6.25	2	ACS	12.5	12.5	12.5		12.5
218	Gyro 2 Power	6.25	2	ACS	12.5	12.5	12.5		12.5
219	Earth Sensor Power	6.25	2	ACS	12.5	12.5	12.5		12.5
220	Articulating Motor Power	6.25	2	ACS	12.5	12.5	12.5		12.5

ID	Analog/Bilevel Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
221	GPS Receiver 1 Power	6.25	2	ACS	12.5		12.5		
222	GPS Receiver 1 Temperature	6.25	8	ACS	50		50		
223	GPS Receiver 2 Power	6.25	2	ACS	12.5		12.5		
224	GPS Receiver 2 Temperature	6.25	8	ACS	50		50		
225	Star Tracker 1 Temperature	6.25	8	ACS	50	50	50		50
226	Star Tracker 1 Tempertature	6.25	8	ACS	50	50	50		50
227	Coarse Sun Sensor 1 Temperature	6.25	8	ACS	50	50	50		50
228	Coarse Sun Sensor 2 Temperature	6.25	8	ACS	50	50	50		50
229	Coarse Sun Sensor 3 Temperature	6.25	8	ACS	50	50	50		50
230	Gyro 1 Temperature	6.25	8	ACS	50	50	50		50
231	Gyro 2 Temperature	6.25	8	ACS	50	50	50		50
232	Earth Sensor Temperature	6.25	8	ACS	50	50	50		50
233	Articulating Motor Temperature	6.25	8	ACS	50	50	50		50
234	Articluating Motor Armature Current	6.25	8	ACS	50	50	50		50
235	Articluating Motor Position	6.25	8	ACS	50	50	50		50
236	Coarse Sun Sensor 4 Power	6.25	2	ACS	12.5	12.5	12.5		12.5
237	ACS Power On/Off (pre sep)	6.25	2	ACS	12.5	12.5	12.5		12.5
238	ACS Power On/Off	6.25	2	ACS	12.5	12.5	12.5		12.5
239	ACS Power Status	6.25	2	ACS	12.5	12.5	12.5		12.5
240	Horizon Scanners On/Off	6.25	2	ACS	12.5	12.5	12.5		12.5
241	Reaction Wheel 1 Power On/Off	6.25	2	ACS	12.5	12.5	12.5		12.5
242	Reaction Wheel 2 Power On/Off	6.25	2	ACS	12.5	12.5	12.5		12.5
243	Reaction Wheel 3 Power On/Off	6.25	2	ACS	12.5	12.5	12.5		12.5
244	Reaction Wheel 4 Power On/Off	6.25	2	ACS	12.5	12.5	12.5		12.5
245	Omega S Telemetry	6.25	8	ACS	50	50	50		50
246	Omega C Telemetry	6.25	8	ACS	50	50	50		50

ID	Analog/Bilevel Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
247	Torque Rod 1 Current (x)	6.25	8	ACS	50	50	50		50
248	Torque Rod 1 Current (y)	6.25	8	ACS	50	50	50		50
249	Torque Rod 1 Current (z)	6.25	8	ACS	50	50	50		50
250	Torque Rod 2 Current (x)	6.25	8	ACS	50	50	50		50
251	Torque Rod 2 Current (y)	6.25	8	ACS	50	50	50		50
252	Torque Rod 2 Current (z)	6.25	8	ACS	50	50	50		50
253	Torque Rod 3 Current (x)	6.25	8	ACS	50	50	50		50
254	Torque Rod 3 Current (y)	6.25	8	ACS	50	50	50		50
255	Torque Rod 3 Current (z)	6.25	8	ACS	50	50	50		50
256	Mag Field (x) from Magnetometer 1	6.25	12	ACS	75	75	75		75
257	Mag Field (y) from Magnetometer 1	6.25	12	ACS	75	75	75		75
258	Mag Field (z) from Magnetometer 1	6.25	12	ACS	75	75	75		75
259	Mag Field (x) from Magnetometer 2	6.25	12	ACS	75	75	75		75
260	Mag Field (y) from Magnetometer 2	6.25	12	ACS	75	75	75		75
261	Mag Field (z) from Magnetometer 2	6.25	12	ACS	75	75	75		75
262	Mag Field (x) from Int. Assy.	6.25	8	ACS	50	50	50		50
263	Mag Field (y) from Int. Assy.	6.25	8	ACS	50	50	50		50
264	Mag Field (z) from Int. Assy.	6.25	8	ACS	50	50	50		50
265	Torque Rod Driver Temperature (y)	6.25	8	ACS	50	50	50		50
266	CP2 Power Supply Temperature	6.25	8	ACS	50	50	50		50
267	Horizon Sensor 1 Temperature (electronics)	6.25	8	ACS	50	50	50		50
268	Mag Sensor Temperature	6.25	8	ACS	50	50	50		50
269	Magnetic Electronics	6.25	8	ACS	50	50	50		50

ID	Analog/Bilevel Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
	Temperature								
270	Reaction Wheel Power Electronics Temperature	6.25	8	ACS	50	50	50		50
271	Reaction Wheel Bearing Temperature	6.25	8	ACS	50	50	50		50
272	HS 2 Head Assembly Temperature	6.25	8	ACS	50	50	50		50
273	Main Bus Voltage	6.25	8	EPS	50	50	50		50
274	PDU 1 Temperature	6.25	8	EPS	50		50		50
275	PDU 2 Temperature	6.25	8	EPS	50		50		50
276	PDU 1 Current	6.25	8	EPS	50		50		50
277	PDU 2 Current	6.25	8	EPS	50		50		50
278	Bus Current Monitor	6.25	8	EPS	50	50	50		50
279	PCU Undervoltage Enbl/Dsbl	6.25	8	EPS	50	50	50		50
280	PCU Temperature	6.25	8	EPS	50	50	50		50
281	PCU PS A +12V Monitor	6.25	8	EPS	50	50	50		50
282	PCU PS B +12V Monitor	6.25	8	EPS	50	50	50		50
283	PCU PS A -12V Monitor	6.25	8	EPS	50	50	50		50
284	PCU PS B -12V Monitor	6.25	8	EPS	50	50	50		50
285	Load Bank 1 Temperature	6.25	8	EPS	50	50	50		50
286	Load Bank 2 Temperature	6.25	8	EPS	50	50	50		50
287	Load Bank 3 Temperature	6.25	8	EPS	50	50	50		50
288	Load Bank 1 Current	6.25	8	EPS	50	50	50		50
289	Load Bank 2 Current	6.25	8	EPS	50	50	50		50
290	Load Bank 3 Current	6.25	8	EPS	50	50	50		50
291	Battery 1 Voltage	6.25	8	EPS	50	50	50		50
292	Battery 2 Voltage	6.25	8	EPS	50	50	50		50
293	Battery 1 Temperature	6.25	8	EPS	50	50	50		50
294	Battery 2 Temperature	6.25	8	EPS	50	50	50		50
295	Battery 1 Current Monitor	6.25	8	EPS	50	50	50		50
296	Battery 2 Current Monitor	6.25	8	EPS	50	50	50		50
297	Battery 1 Cell Balance	6.25	8	EPS	50	50	50		50

ID	Analog/Bilevel Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
298	Battery 2 Cell Balance	6.25	8	EPS	50	50	50		50
299	Battery 1 Charge Relay Status	6.25	2	EPS	12.5		12.5		12.5
300	Battery 2 Charge Relay Status	6.25	2	EPS	12.5		12.5		12.5
301	Battery 1 Cell Failure Enbl/Dsbl	6.25	2	EPS	12.5		12.5		12.5
302	Battery 2 Cell Failure Enbl/Dsbl	6.25	2	EPS	12.5		12.5		12.5
303	V/T A5 Relay Status	6.25	2	EPS	12.5		12.5		12.5
304	V/T A6 Relay Status	6.25	2	EPS	12.5		12.5		12.5
305	V/T A7 Relay Status	6.25	2	EPS	12.5		12.5		12.5
306	Overall V/T Relay Status	6.25	2	EPS	12.5		12.5		12.5
307	Solar Array Current Monitor	6.25	8	EPS	50		50		50
308	Solar Array Circiut On/Off	6.25	2	EPS	12.5		12.5		12.5
309	Solar Array Shorting Plug Status	6.25	2	EPS	12.5		12.5		12.5
310	Battery 1/Compartment 1B Delta Temperature	6.25	2	EPS	12.5		12.5		12.5
311	Battery 2/Compartment 1B Delta Temperature	6.25	2	EPS	12.5		12.5		12.5
312	Solary Array (Bus/Battery) Current Sum	6.25	2	EPS	12.5		12.5		12.5
313	Battery Current Sum	6.25	2	EPS	12.5		12.5		12.5
314	NEB Bypass On/Off	6.25	2	EPS	12.5		12.5		12.5
315	NEB Bypass Enbl/Dsbl	6.25	2	EPS	12.5		12.5		12.5
316	Laser Beacon Low Power On/Off	6.25	2	EPS	12.5		12.5		12.5
317	Laser Beacon High Power On/Off	6.25	2	EPS	12.5		12.5		12.5
318	Compartment 1 Heater On/Off	6.25	2	TCS	12.5		12.5		
319	Compartment 2 Heater On/Off	6.25	2	TCS	12.5		12.5		
320	Compartment 3 Heater On/Off	6.25	2	TCS	12.5		12.5		
321	Compartment 4 Heater On/Off	6.25	2	TCS	12.5		12.5		

ID	Analog/Bilevel Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
322	Compartment Heater Status	6.25	2	TCS	12.5		12.5		
323	Retroreflector 2W Heater On/Off	6.25	2	TCS	12.5		12.5		
324	Retroreflector 3W Heater On/Off	6.25	2	TCS	12.5		12.5		
325	Compartment 1A Temperature	6.25	2	TCS	12.5		12.5		
326	Compartment 1B Temperature	6.25	2	TCS	12.5		12.5		
327	Compartment 2A Temperature	6.25	2	TCS	12.5		12.5		
328	Compartment 2B Temperature	6.25	2	TCS	12.5		12.5		
329	Compartment 3A Temperature	6.25	2	TCS	12.5		12.5		
330	Compartment 3B Temperature	6.25	2	TCS	12.5		12.5		
331	Compartment 4A Temperature	6.25	2	TCS	12.5		12.5		
332	Compartment 4B Temperature	6.25	2	TCS	12.5		12.5		
333	Compartment 1 Radiator Temperature	6.25	2	TCS	12.5		12.5		
334	Compartment 2 Radiator Temperature	6.25	2	TCS	12.5		12.5		
335	Compartment 3 Radiator Temperature	6.25	2	TCS	12.5		12.5		
336	Compartment 4 Radiator Temperature	6.25	2	TCS	12.5		12.5		
337	Flexure Bracket 1/2 Temperature	6.25	2	TCS	12.5		12.5		
338	Flexure Bracket 2/3 Temperature	6.25	2	TCS	12.5		12.5		
339	Flexure Bracket 3/4 Temperature	6.25	2	TCS	12.5		12.5		
340	Flexure Bracket 4/1 Temperature	6.25	2	TCS	12.5		12.5		
341	Solar Array Panel 0 Temperature	6.25	2	TCS	12.5		12.5		
342	Solar Array Panel 60 Temperature	6.25	2	TCS	12.5		12.5		

ID	Analog/Bilevel Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
343	Solar Array Panel 120 Temperature	6.25	2	TCS	12.5		12.5		
344	Solar Array Panel 180 Temperature	6.25	2	TCS	12.5		12.5		
345	Solar Array Panel 240 Temperature	6.25	2	TCS	12.5		12.5		
346	Solar Array Panel 300 Temperature	6.25	2	TCS	12.5		12.5		
347	Solar Array Deck Temperature (1)	6.25	2	TCS	12.5		12.5		
348	Solar Array Deck Temperature (2)	6.25	2	TCS	12.5		12.5		
349	Laser Diode Assembly Temperature	6.25	2	TCS	12.5		12.5		
350	Retroreflector Temperature (T516)	6.25	8	TCS	50		50		
351	Retroreflector Temperature (T517)	6.25	8	TCS	50		50		
352	Retroreflector Temperature (T518)	6.25	8	TCS	50		50		
353	Retroreflector Temperature (T519)	6.25	8	TCS	50		50		
354	SP Thermistor 1	6.25	8	WAVE	50	50		50	
355	SP Thermistor 2	6.25	8	WAVE	50	50		50	
356	EP Thermistor 1	6.25	8	WAVE	50	50		50	
357	EP Thermistor 2	6.25	8	WAVE	50	50		50	
358	ADS Instrumentation Group Monitor 1 (+15V)	6.25	8	WAVE	50	50		50	
359	ADS Instrumentation Group Monitor 2 (-15V)	6.25	8	WAVE	50	50		50	
360	MHD Instrumentation Group Monitor 1 (+15V)	6.25	8	WAVE	50	50		50	
361	MHD Instrumentation Group Monitor 2 (-15V)	6.25	8	WAVE	50	50		50	
362	Accelerometer Instrumentation Group Moitor 1 (+15V)	6.25	8	WAVE	50	50		50	
363	Secondary Power	6.25	8	WAVE	50	50		50	

ID	Analog/Bilevel Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
	Supply Monitor 1								
364	Secondary Power Supply Monitor 2	6.25	8	WAVE	50	50		50	
365	WAVE Encoder On/Off	6.25	2	WAVE	12.5	12.5		12.5	
366	PCM Format Selection	6.25	2	WAVE	12.5	12.5		12.5	
367	Data Rate Selection	6.25	2	WAVE	12.5	12.5		12.5	
368	ADS Power On/Off	6.25	2	WAVE	12.5	12.5		12.5	
369	MHD Power On/Off	6.25	2	WAVE	12.5	12.5		12.5	
370	ACC Power On/Off	6.25	2	WAVE	12.5	12.5		12.5	
371	Clock Select Status	6.25	2	WAVE	12.5	12.5		12.5	
372	TDU WAVE Format Selection	6.25	2	WAVE	12.5	12.5		12.5	
373	TDU WAVE Data Rate Selection	6.25	2	WAVE	12.5	12.5		12.5	
374	TDU WAVE ADS Power On/Off	6.25	2	WAVE	12.5	12.5		12.5	
375	TDU WAVE MHD Power On/Off	6.25	2	WAVE	12.5	12.5		12.5	
376	TDU WAVE ACC Power On/Off	6.25	2	WAVE	12.5	12.5		12.5	
377	TDU WAVE Clock Select Status	6.25	2	WAVE	12.5	12.5		12.5	
378	Propellant Tank Temperature	6.25	8	PROP	50		50		
379	Propellant Line 1 Temperature	6.25	8	PROP	50		50		
380	Propellant Line 2 Temperature	6.25	8	PROP	50		50		
381	Propellant Line 3 Temperature	6.25	8	PROP	50		50		
382	Propellant Line 4 Temperature	6.25	8	PROP	50		50		
383	Valve 1 Position	6.25	2	PROP	12.5		12.5		
384	Valve 2 Position	6.25	2	PROP	12.5		12.5		
385	Valve 3 Position	6.25	2	PROP	12.5		12.5		
386	Valve 4 Position	6.25	2	PROP	12.5		12.5		
387	Blow Down Tank Pressure	6.25	8	PROP	50		50		
388	Serial Digital Spare				0				
389	Serial Digital Spare				0				
390	Serial Digital Spare				0				
391	Serial Digital Spare				0				
392	Serial Digital Spare				0				
393	Analog Spare	6.25	8		50		50		

ID	Analog/Bilevel Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
394	Analog Spare	6.25	8		50		50		
395	Analog Spare	6.25	8		50		50		
396	Analog Spare	6.25	8		50		50		
397	Analog Spare	6.25	8		50		50		
398	Analog Spare	6.25	8		50		50		
399	Analog Spare	6.25	8		50		50		
400	Analog Spare	6.25	8		50		50		
401	Analog Spare	6.25	8		50		50		
402	Analog Spare	6.25	8		50		50		
403	Analog Spare	6.25	8		50		50		
404	Analog Spare	6.25	8		50		50		
405	Analog Spare	6.25	8		50		50		
406	Analog Spare	6.25	8		50		50		
407	Analog Spare	6.25	8		50		50		
408	Analog Spare	6.25	8		50		50		
409	Analog Spare	6.25	8		50		50		
410	Analog Spare	6.25	8		50		50		
411	Analog Spare	6.25	8		50		50		
412	Analog Spare	6.25	8		50		50		
413	Analog Spare	6.25	8		50		50		
414	Analog Spare	6.25	8		50		50		
415	Analog Spare	6.25	8		50		50		
416	Analog Spare	6.25	8		50		50		
417	Analog Spare	6.25	8		50		50		
418	Bilevel Spare	6.25	2		12.5	12.5	12.5		
419	Bilevel Spare	6.25	2		12.5	12.5	12.5		
420	Bilevel Spare	6.25	2		12.5	12.5	12.5		
421	Bilevel Spare	6.25	2		12.5	12.5	12.5		
422	Bilevel Spare	6.25	2		12.5	12.5	12.5		
423	Bilevel Spare	6.25	2		12.5	12.5	12.5		
	TOTAL BIT RATE [bps]:					233576.9	9676.952	227075	3900

ID	Serial/Digital Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
1	Coarse Scan	6.25	1	PEP/ECP	6.25	6.25		6.25	
2	Fine Scan	6.25	1	PEP/ECP	6.25	6.25		6.25	
3	Closed Loop Point	6.25	1	PEP/ECP	6.25	6.25		6.25	
4	Aimpoint Compensation	6.25	1	PEP/ECP	6.25	6.25		6.25	
5	Mirror Alignment	6.25	1	PEP/EC	6.25	6.25		6.25	

ID	Serial/Digital Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
	Bias			P					
6	Perform Transform	6.25	1	PEP/ECP	6.25	6.25		6.25	
7	Closed Loop Quad Cell Calibration	6.25	1	PEP/ECP	6.25	6.25		6.25	
8	Aimpoint Compensation Pulse	6.25	1	PEP/ECP	6.25	6.25		6.25	
9	Spare	6.25	6	PEP/ECP	37.5	37.5		37.5	
10	Command Accept Counter	6.25	8	PEP/ECP	50	50		50	
11	Command Reject Counter	6.25	8	PEP/ECP	50	50		50	
12	TSS Hit Detector Counter	6.25	8	PEP/ECP	50	50		50	
13	XMT FSM Cage Status	6.25	2	PEP/ECP	12.5	12.5	12.5	12.5	
14	XMT RM1 Cage Status	6.25	2	PEP/ECP	12.5	12.5	12.5	12.5	
15	XMT RM2 Cage Status	6.25	2	PEP/ECP	12.5	12.5	12.5	12.5	
16	XMT RM3 Cage Status	6.25	2	PEP/ECP	12.5	12.5	12.5	12.5	
17	XMT RM4 Cage Status	6.25	2	PEP/ECP	12.5	12.5	12.5	12.5	
18	RCV FSM Cage Status	6.25	2	PEP/ECP	12.5	12.5	12.5	12.5	
19	RCV RM1 Cage Status	6.25	2	PEP/ECP	12.5	12.5	12.5	12.5	
20	RCV RM2 Cage Status	6.25	2	PEP/ECP	12.5	12.5	12.5	12.5	
21	RCV RM3 Cage Status	6.25	2	PEP/ECP	12.5	12.5	12.5	12.5	
22	RCV RM4 Cage Status	6.25	2	PEP/ECP	12.5	12.5	12.5	12.5	
23	Self Test Lamp Status	6.25	1	PEP/ECP	6.25	6.25		6.25	
24	Source FPS Beacon	6.25	1	PEP/ECP	6.25	6.25		6.25	
25	Target FPS Beacon	6.25	1	PEP/ECP	6.25	6.25		6.25	
26	ROM Status	6.25	1	PEP/ECP	6.25	6.25		6.25	
27	Timer Status	6.25	1	PEP/ECP	6.25	6.25		6.25	
28	Initialization Results	6.25	1	PEP/EC	6.25	6.25		6.25	

ID	Serial/Digital Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
				P					
29	Self Check Results	6.25	1	PEP/ECP	6.25	6.25		6.25	
30	CAS Initialization Results	6.25	1	PEP/ECP	6.25	6.25		6.25	
31	Initialization Mode	25	1	PEP/ECP	25	25		25	
32	Standby Mode	25	1	PEP/ECP	25	25		25	
33	Quad Cell Calibraion Mode	25	1	PEP/ECP	25	25		25	
34	Self Check Mode	25	1	PEP/ECP	25	25		25	
35	Table Upload	25	1	PEP/ECP	25	25		25	
36	Table Download	25	1	PEP/ECP	25	25		25	
37	CP1/CAS Code Transfer	25	1	PEP/ECP	25	25		25	
38	CP1 APC Table Generation	25	1	PEP/ECP	25	25		25	
39	CP2/CAS Code Transfer	25	1	PEP/ECP	25	25		25	
40	CP2 APC Table Generation	25	1	PEP/ECP	25	25		25	
41	EEPROM Self Check Status	6.25	8	PEP/ECP	50	50	50	50	
42	RAM Self Check Status	6.25	8	PEP/ECP	50	50	50	50	
43	Beacon Acuisition and Track Mode	6.25	1	PEP/ECP	6.25	6.25	6.25	6.25	
44	Coarse Scan Mode	6.25	1	PEP/ECP	6.25	6.25	6.25	6.25	
45	Backup to Coarse Hit	6.25	1	PEP/ECP	6.25	6.25	6.25	6.25	
46	Fine Scan Mode	6.25	1	PEP/ECP	6.25	6.25	6.25	6.25	
47	Closed Loop Point Mode	6.25	1	PEP/ECP	6.25	6.25	6.25	6.25	
48	Open Loop Point Mode	6.25	1	PEP/ECP	6.25	6.25	6.25	6.25	
49	Beacon Dropout Resolution	6.25	1	PEP/ECP	6.25	6.25		6.25	
50	Spare	6.25	1	PEP/ECP	6.25	6.25		6.25	
51	CAS Initialization	6.25	1	PEP/EC	6.25	6.25	6.25	6.25	

ID	Serial/Digital Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
	Mode			P					
52	CAS Calibration Table Dump Mode	6.25	1	PEP/EC P	6.25	6.25	6.25	6.25	
53	CAS Self Check Mode	6.25	1	PEP/EC P	6.25	6.25	6.25	6.25	
54	CAS Standby Mode	6.25	1	PEP/EC P	6.25	6.25	6.25	6.25	
55	CAS Acquisition Mode	6.25	1	PEP/EC P	6.25	6.25	6.25	6.25	
56	CAS Reacquisition Mode	6.25	1	PEP/EC P	6.25	6.25	6.25	6.25	
57	CAS Detector Test Mode	6.25	2	PEP/EC P	12.5	12.5	12.5	12.5	
58	CP1 Post Handoff Quad Cell Calibration	6.25	1	PEP/EC P	6.25	6.25	6.25	6.25	
59	CP1 S/W Set Self Check Gain	6.25	1	PEP/EC P	6.25	6.25	6.25	6.25	
60	CP1 S/W Set Engagement Gain	6.25	1	PEP/EC P	6.25	6.25	6.25	6.25	
61	CP2 Post Handoff Quad Cell Calibration	6.25	1	PEP/EC P	6.25	6.25	6.25	6.25	
62	CP2 S/W Set Self Check Gain	6.25	1	PEP/EC P	6.25	6.25	6.25	6.25	
63	CP2 S/W Set Engagement Gain	6.25	1	PEP/EC P	6.25	6.25	6.25	6.25	
64	CAS Track/Monitor Mode	6.25	1	PEP/EC P	6.25	6.25	6.25	6.25	
65	CAS Alignment Mode	6.25	1	PEP/EC P	6.25	6.25	6.25	6.25	
66	CAS Code Receive State	6.25	1	PEP/EC P	6.25	6.25	6.25	6.25	
67	CP1/CAS Memory Dump	6.25	1	PEP/EC P	6.25	6.25	6.25	6.25	
68	CP1/CAS Code Transfer Pass/Fail	6.25	1	PEP/EC P	6.25	6.25	6.25	6.25	
69	CP2/CAS Memory Dump	6.25	1	PEP/EC P	6.25	6.25	6.25	6.25	
70	CP2/CAS Code Transfer Pass/Fail	6.25	1	PEP/EC P	6.25	6.25	6.25	6.25	
71	Target CAS Beacon Presence	6.25	1	PEP/EC P	6.25	6.25	6.25	6.25	
72	Target CAS Beacon Track Status	6.25	1	PEP/EC P	6.25	6.25	6.25	6.25	
73	Source CAS Beacon Presence	6.25	1	PEP/EC P	6.25	6.25	6.25	6.25	
74	Source CAS Beacon	6.25	1	PEP/EC	6.25	6.25	6.25	6.25	

ID	Serial/Digital Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
	Track Status			P					
75	Target FPS Beacon Detect Status	6.25	1	PEP/ECP	6.25	6.25	6.25	6.25	
76	Target FPS Beacon Presence	6.25	1	PEP/ECP	6.25	6.25	6.25	6.25	
77	Source FPS Beacon Detect Status	6.25	1	PEP/ECP	6.25	6.25	6.25	6.25	
78	Source FPS Beacon Presence	6.25	1	PEP/ECP	6.25	6.25	6.25	6.25	
79	RM/OM Servo Output - X position	25	16	PEP/ECP	400	400		400	
80	RM/OM Servo Output - Y Position	25	16	PEP/ECP	400	400		400	
81	TSS Closed Loop Uplink - X position	25	16	PEP/ECP	400	400		400	
82	TSS Closed Loop Uplink - Y position	25	16	PEP/ECP	400	400		400	
83	TSS Hit Detector Status	25	4	PEP/ECP	100	100		100	
84	TSS Hit Offset Counter	25	4	PEP/ECP	100	100		100	
85	Target Pitch Servo Loop Gain	6.25	3	PEP/ECP	18.75	18.75		18.75	
86	Target Yaw Servo Loop Gain	6.25	3	PEP/ECP	18.75	18.75		18.75	
87	Source Pitch Servo Loop Gain	6.25	3	PEP/ECP	18.75	18.75		18.75	
88	Source Yaw Servo Loop Gain	6.25	3	PEP/ECP	18.75	18.75		18.75	
89	CP1 Table Upload Byte Count	6.25	1	PEP/ECP	6.25	6.25	6.25	6.25	
90	CP2 Table Upload Byte Count	6.25	1	PEP/ECP	6.25	6.25	6.25	6.25	
91	PEP Table Upload Offset	6.25	1	PEP/ECP	6.25	6.25	6.25	6.25	
92	PEP Table Upload ID	6.25	1	PEP/ECP	6.25	6.25	6.25	6.25	
93	Command Accept Counter		8	ACS/ACP	0	0	0		0
94	Command Reject Counter		8	ACS/ACP	0	0	0		0
95	Roll/Yaw Enable/Disable Flag	6.25	1	ACS/ACP	6.25	6.25	6.25		6.25
96	Sun Pitch Enable/Disable Flag	6.25	1	ACS/ACP	6.25	6.25	6.25		6.25
97	Timer Reset Flag	6.25	1	ACS/A	6.25	6.25	6.25		6.25

ID	Serial/Digital Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
				CP					
98	CPU Self Check Status	6.25	1	ACS/A CP	6.25	6.25	6.25		6.25
99	ADC Self check Status	6.25	1	ACS/A CP	6.25	6.25	6.25		6.25
100	Parallel I/O Self Check Status	6.25	1	ACS/A CP	6.25	6.25	6.25		6.25
101	ROM Self Check Status	6.25	1	ACS/A CP	6.25	6.25	6.25		6.25
102	Self Check Flag	6.25	1	ACS/A CP	6.25	6.25	6.25		6.25
103	CP2 Background Self Check Status	6.25	2	ACS/A CP	12.5	12.5	12.5		12.5
104	CP2 Self Check Status	6.25	5	ACS/A CP	31.25	31.25	31.25		31.25
105	CP1 Background Self Check Status	6.25	2	ACS/A CP	12.5	12.5	12.5		12.5
106	CP1 Self Check Status	6.25	5	ACS/A CP	31.25	31.25	31.25		31.25
107	EEPROM Self Check Status	6.25	8	ACS/A CP	50	50	50		50
108	GPS Receiver 1 Lat/Long	6.25	8	ACS/A CP	50	50	50		50
109	GPS Receiver 1 Time	6.25	8	ACS/A CP	50	50	50		50
110	GPS Receiver 2 Lat/Long	6.25	8	ACS/A CP	50	50	50		50
111	GPS Receiver 2 Time	6.25	8	ACS/A CP	50	50	50		50
112	RAM Self Check Status	6.25	8	ACS/A CP	50	50	50		50
113	CP2 Kalman Mode	6.25	1	ACS/A CP	6.25	6.25	6.25		6.25
114	CP2 Filter Mode	6.25	1	ACS/A CP	6.25	6.25	6.25		6.25
115	CP1 Kalman Mode	6.25	1	ACS/A CP	6.25	6.25	6.25		6.25
116	CP1 Filter Mode	6.25	1	ACS/A CP	6.25	6.25	6.25		6.25
117	Ephemeris Vector Update Status	6.25	1	ACS/A CP	6.25	6.25	6.25		6.25
118	CP2 Integrator Status	6.25	1	ACS/A CP	6.25	6.25	6.25		6.25
119	CP1 Integrator Status	6.25	1	ACS/A CP	6.25	6.25	6.25		6.25
120	Horizon Sensor 1	6.25	1	ACS/A	6.25	6.25	6.25		6.25

ID	Serial/Digital Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
	Timing Status			CP					
121	Horizon Sensor 2 Timing Status	6.25	1	ACS/A CP	6.25	6.25	6.25		6.25
122	Horizon Sensor 1 Interrupt Status	6.25	1	ACS/A CP	6.25	6.25	6.25		6.25
123	Horizon Sensor 2 Interrupt Status	6.25	1	ACS/A CP	6.25	6.25	6.25		6.25
124	HS 1 Mode	6.25	1	ACS/A CP	6.25	6.25	6.25		6.25
125	HS 1 Diagnostic/Data Value	6.25	4	ACS/A CP	25	25	25		25
126	HS 2 Mode	6.25	1	ACS/A CP	6.25	6.25	6.25		6.25
127	HS 2 Diagnostic/Data Value	6.25	4	ACS/A CP	25	25	25		25
128	ACS Table Upload Flag	6.25	1	ACS/A CP	6.25	6.25	6.25		6.25
129	Magnetometer 1 Bz Data Valid	6.25	1	ACS/A CP	6.25	6.25	6.25		6.25
130	Magnetometer 1 By Data Valid	6.25	1	ACS/A CP	6.25	6.25	6.25		6.25
131	Magnetometer 1 Bx Data Valid	6.25	1	ACS/A CP	6.25	6.25	6.25		6.25
132	Magnetometer 1 x,y,z Data Valid	6.25	3	ACS/A CP	18.75	18.75	18.75		18.75
133	Magnetometer 2 Bz Data Valid	6.25	1	ACS/A CP	6.25	6.25	6.25		6.25
134	Magnetometer 2 By Data Valid	6.25	1	ACS/A CP	6.25	6.25	6.25		6.25
135	Magnetometer 2 Bx Data Valid	6.25	1	ACS/A CP	6.25	6.25	6.25		6.25
136	Magnetometer 2 x,y,z Data Valid	6.25	3	ACS/A CP	18.75	18.75	18.75		18.75
137	Roll HS Configuration	6.25	2	ACS/A CP	12.5	12.5	12.5		12.5
138	Pitch HS Configuration	6.25	1	ACS/A CP	6.25	6.25	6.25		6.25
139	ACS Table Dump Flag	6.25	1	ACS/A CP	6.25	6.25	6.25		6.25
140	Sunbathing Mode Enbl/Dsbl	6.25	1	ACS/A CP	6.25	6.25	6.25		6.25
141	Engagement Mode Enbl/Dsbl	6.25	1	ACS/A CP	6.25	6.25	6.25		6.25
142	Tracking Mode Enbl/Dsbl	6.25	1	ACS/A CP	6.25	6.25	6.25		6.25
143	ACS Mode Status	6.25	6	ACS/A	37.5	37.5	37.5		37.5

ID	Serial/Digital Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
				CP					
144	Roll Error	6.25	8	ACS/A CP	50	50	50		50
145	Pitch Error	6.25	8	ACS/A CP	50	50	50		50
146	Yaw Error	6.25	8	ACS/A CP	50	50	50		50
147	Calculated X Body Torque	6.25	8	ACS/A CP	50	50	50		50
148	Calculated Y Body Torque	6.25	8	ACS/A CP	50	50	50		50
149	Calculated Z Body Torque	6.25	8	ACS/A CP	50	50	50		50
150	X Body Rate from Kalman Filter	6.25	8	ACS/A CP	50	50	50		50
151	Z Body Rate from Dalman Filter	6.25	8	ACS/A CP	50	50	50		50
152	Reaction Wheel 1 Speed	6.25	8	ACS/A CP	50	50	50		50
153	Reaction Wheel 2 Speed	6.25	8	ACS/A CP	50	50	50		50
154	Reaction Wheel 3 Speed	6.25	8	ACS/A CP	50	50	50		50
155	Reaction Wheel 4 Speed	6.25	8	ACS/A CP	50	50	50		50
156	Yaw Bias Estimate	6.25	8	ACS/A CP	50	50	50		50
157	HS1 Chord Angle	6.25	16	ACS/A CP	100	100	100		100
158	HS1 Phase Angle	6.25	16	ACS/A CP	100	100	100		100
159	HS2 Chord Angle	6.25	16	ACS/A CP	100	100	100		100
160	HS2 Phase Angle	6.25	16	ACS/A CP	100	100	100		100
161	Heading Angle	6.25	16	ACS/A CP	100	100	100		100
162	Longitude	6.25	16	ACS/A CP	100	100	100		100
163	Orbit Rate	6.25	16	ACS/A CP	100	100	100		100
164	CO Lattitude	6.25	16	ACS/A CP	100	100	100		100
165	Argument of Latitude	6.25	16	ACS/A CP	100	100	100		100
166	Comp East	6.25	16	ACS/A	100	100	100		100

ID	Serial/Digital Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
	Component of Magnetic Field			CP					
167	Comp South Component of Magnetic Field	6.25	16	ACS/ACP	100	100	100		100
168	Pitch Angle Command	6.25	16	ACS/ACP	100	100	100		100
169	Pitch Rate Command	6.25	16	ACS/ACP	100	100	100		100
170	Roll Angle	6.25	16	ACS/ACP	100	100	100		100
171	Pitch Angle Command	6.25	16	ACS/ACP	100	100	100		100
172	Yaw Angle from Kalman Filter	6.25	16	ACS/ACP	100	100	100		100
173	Yaw Angle from Magnetometer	6.25	16	ACS/ACP	100	100	100		100
174	Roll Angle Rate	6.25	derived	ACS/ACP			0		0
175	Pitch Angle Rate	6.25	derived	ACS/ACP			0		0
176	Yaw Angle Rate (Kalman)	6.25	derived	ACS/ACP			0		0
177	Current ACP Clock Reading	6.25	32	ACS/ACP	200	200	200		200
178	ACP Enable Flag Composite	6.25	4	ACS/ACP	25	25			25
179	FIFO Reset Test Status	100	1	PEP/CAS	100	100		100	
180	Floating Point Test Status	100	1	PEP/CAS	100	100		100	
181	Memory Test Status	100	1	PEP/CAS	100	100		100	
182	DAU Test Status	100	1	PEP/CAS	100	100		100	
183	FPA Test Status	100	1	PEP/CAS	100	100		100	
184	DAC/MUX, ADC Test Status	100	1	PEP/CAS	100	100		100	
185	ECP Test Status	100	1	PEP/CAS	100	100		100	
186	CAS TLM Format	100	1	PEP/CAS	100	100		100	
187	CAS Mode Status	100	3	PEP/CAS	300	300		300	
188	CAS Operational	100	12	PEP/CA	1200	1200		1200	

ID	Serial/Digital Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
	States			S					
189	CAS Target X Position	100	12	PEP/CA S	1200	1200		1200	
190	CAS Target Y Position	100	12	PEP/CA S	1200	1200		1200	
191	CAS Target Search Queue	100	12	PEP/CA S	1200	1200		1200	
192	CAS Target Track Intensity	100	12	PEP/CA S	1200	1200		1200	
193	CAS Source X Position	100	12	PEP/CA S	1200	1200		1200	
194	CAS Source Y Position	100	12	PEP/CA S	1200	1200		1200	
195	CAS Source Search Queue	100	12	PEP/CA S	1200	1200		1200	
196	CAS Source Track Intensity	100	12	PEP/CA S	1200	1200		1200	
197	XMT RM X DAC Voltage	6.25	12	PEP/CA S	75	75	75	75	
198	XMT RM Y DAC Voltage	6.25	12	PEP/CA S	75	75	75	75	
199	XMT FSM X DAC Voltage	6.25	12	PEP/CA S	75	75	75	75	
200	XMT FSM Y DAC Voltage	6.25	12	PEP/CA S	75	75	75	75	
201	XMT OM X DAC Voltage	6.25	12	PEP/CA S	75	75	75	75	
202	XMT OM Y DAC Voltage	6.25	12	PEP/CA S	75	75	75	75	
203	RCV RM X DAC Voltage	6.25	12	PEP/CA S	75	75	75	75	
204	RCV RM Y DAC Voltage	6.25	12	PEP/CA S	75	75	75	75	
205	RCV FSM X DAC Voltage	6.25	12	PEP/CA S	75	75	75	75	
206	RCV FSM Y DAC Voltage	6.25	12	PEP/CA S	75	75	75	75	
207	RCV OM X DAC Voltage	6.25	12	PEP/CA S	75	75	75	75	
208	RCV OM Y DAC Voltage	6.25	12	PEP/CA S	75	75	75	75	
209	Target FPS Threshold DAC Voltage	6.25	12	PEP/CA S	75	75	75	75	
210	Source FPS Threshold DAC Voltage	6.25	12	PEP/CA S	75	75	75	75	
211	RCV OM Y Constant	6.25	12	PEP/CA	75	75	75	75	

ID	Serial/Digital Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
	Bias DAC Voltage			S					
212	RCV OM X Constant Bias DAC Voltage	6.25	12	PEP/CAS	75	75	75	75	
213	Spare	6.25	12	PEP/CAS	75	75		75	
214	Spare	6.25	12	PEP/CAS	75	75		75	
215	XMT RM X DIT Position	6.25	12	PEP/CAS	75	75		75	
216	XMT RM Y DIT Position	6.25	12	PEP/CAS	75	75		75	
217	XMT FSM X DIT Position	6.25	12	PEP/CAS	75	75		75	
218	XMT FSM Y DIT Position	6.25	12	PEP/CAS	75	75		75	
219	XMT OM X DIT Position	6.25	12	PEP/CAS	75	75		75	
220	XMT OM Y DIT Position	6.25	12	PEP/CAS	75	75		75	
221	RCV RM X DIT Position	6.25	12	PEP/CAS	75	75		75	
222	RCV RM Y DIT Position	6.25	12	PEP/CAS	75	75		75	
223	RCV FSM X DIT Position	6.25	12	PEP/CAS	75	75		75	
224	RCV FSM Y DIT Position	6.25	12	PEP/CAS	75	75		75	
225	RCV OM X DIT Position	6.25	12	PEP/CAS	75	75		75	
226	RCV OM Y DIT Position	6.25	12	PEP/CAS	75	75		75	
227	Processor Board +5V	6.25	12	PEP/CAS	75	75	75	75	
228	Analog Board +5V	6.25	12	PEP/CAS	75	75	75	75	
229	Analog Board +15V	6.25	12	PEP/CAS	75	75	75	75	
230	Analog Board -5V	6.25	12	PEP/CAS	75	75	75	75	
231	DAC 1 Reference Voltage	6.25	12	PEP/CAS	75	75	75	75	
232	DAC 2 Reference Voltage	6.25	12	PEP/CAS	75	75	75	75	
233	DAC 3 Reference Voltage	6.25	12	PEP/CAS	75	75	75	75	
234	ADC Reference	6.25	12	PEP/CA	75	75	75	75	

ID	Serial/Digital Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
	Voltage			S					
235	Analog Board Temperature	6.25	12	PEP/CAS	75	75	75	75	
236	Processor Board Temperature	6.25	12	PEP/CAS	75	75	75	75	
237	Analog Board Ground	6.25	12	PEP/CAS	75	75	75	75	
238	TFPA Track Pixel 1	6.25	12	PEP/CAS	75	75		75	
239	TFPA Track Pixel 2	6.25	12	PEP/CAS	75	75		75	
240	TFPA Track Pixel 3	6.25	12	PEP/CAS	75	75		75	
241	TFPA Track Pixel 4	6.25	12	PEP/CAS	75	75		75	
242	TFPA Track Pixel 5	6.25	12	PEP/CAS	75	75		75	
243	TFPA Track Pixel 6	6.25	12	PEP/CAS	75	75		75	
244	TFPA Track Pixel 7	6.25	12	PEP/CAS	75	75		75	
245	TFPA Track Pixel 8	6.25	12	PEP/CAS	75	75		75	
246	TFPA Track Pixel 9	6.25	12	PEP/CAS	75	75		75	
247	TFPA Normalization Factor	6.25	12	PEP/CAS	75	75		75	
248	TFPA Track Block X Position	6.25	12	PEP/CAS	75	75		75	
249	TFPA Track Block Y Position	6.25	12	PEP/CAS	75	75		75	
250	SFPA Track Pixel 1	6.25	12	PEP/CAS	75	75		75	
251	SFPA Track Pixel 2	6.25	12	PEP/CAS	75	75		75	
252	SFPA Track Pixel 3	6.25	12	PEP/CAS	75	75		75	
253	SFPA Track Pixel 4	6.25	12	PEP/CAS	75	75		75	
254	SFPA Track Pixel 5	6.25	12	PEP/CAS	75	75		75	
255	SFPA Track Pixel 6	6.25	12	PEP/CAS	75	75		75	
256	SFPA Track Pixel 7	6.25	12	PEP/CAS	75	75		75	
257	SFPA Track Pixel 8	6.25	12	PEP/CA	75	75		75	

ID	Serial/Digital Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
				S					
258	SFPA Track Pixel 9	6.25	12	PEP/CAS	75	75		75	
259	SFPA Normalization Factor	6.25	12	PEP/CAS	75	75		75	
260	SFPA Track Block X Position	6.25	12	PEP/CAS	75	75		75	
261	SFPA Track Block Y Position	6.25	12	PEP/CAS	75	75		75	
262	TFPA Analog Ground	6.25	12	PEP/CAS	75	75	75	75	
263	TFPA +5V	6.25	12	PEP/CAS	75	75	75	75	
264	TFPA +15V	6.25	12	PEP/CAS	75	75	75	75	
265	TFPA -2V	6.25	12	PEP/CAS	75	75	75	75	
266	TFPA -8V	6.25	12	PEP/CAS	75	75	75	75	
267	TFPA -13V	6.25	12	PEP/CAS	75	75	75	75	
268	TFPA -15V	6.25	12	PEP/CAS	75	75	75	75	
269	TFPA -16V	6.25	12	PEP/CAS	75	75	75	75	
270	TFPA -19V	6.25	12	PEP/CAS	75	75	75	75	
271	TFPA -23V	6.25	12	PEP/CAS	75	75	75	75	
272	TFPA CID Temperature	6.25	12	PEP/CAS	75	75	75	75	
273	TFPA Base Temperature	6.25	12	PEP/CAS	75	75	75	75	
274	SFPA Analog Ground	6.25	12	PEP/CAS	75	75	75	75	
275	SFPA +5V	6.25	12	PEP/CAS	75	75	75	75	
276	SFPA +15V	6.25	12	PEP/CAS	75	75	75	75	
277	SFPA -2V	6.25	12	PEP/CAS	75	75	75	75	
278	SFPA -8V	6.25	12	PEP/CAS	75	75	75	75	
279	SFPA -13V	6.25	12	PEP/CAS	75	75	75	75	
280	SFPA -15V	6.25	12	PEP/CA	75	75	75	75	

ID	Serial/Digital Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
				S					
281	SFPA -16V	6.25	12	PEP/CAS	75	75	75	75	
282	SFPA -19V	6.25	12	PEP/CAS	75	75	75	75	
283	SFPA -23V	6.25	12	PEP/CAS	75	75	75	75	
284	SFPA CID Temperature	6.25	12	PEP/CAS	75	75	75	75	
285	SFPA Base Temperature	6.25	12	PEP/CAS	75	75	75	75	
286	CAS Mirror Control Status	6.25	12	PEP/CAS	75	75	75	75	
287	CAS Alignment Mode Flag	6.25	12	PEP/CAS	75	75		75	
288	Source Pixel 1,2,3 Track Block Sum	Derived	Derived	PEP/CAS					
289	Source Pixel 1,4,7 Track Block Sum	Derived	Derived	PEP/CAS					
290	Source Pixel 2,5,8 Track Block Sum	Derived	Derived	PEP/CAS					
291	Source Pixel 3,6,9 Track Block Sum	Derived	Derived	PEP/CAS					
292	Source Pixel 4,5,6 Track Block Sum	Derived	Derived	PEP/CAS					
293	Source Pixel 7,8,9 Track Block Sum	Derived	Derived	PEP/CAS					
294	Source Pixel Total Track Block Sum	Derived	Derived	PEP/CAS					
295	Target Pixel 1,2,3 Track Block Sum	Derived	Derived	PEP/CAS					
296	Target Pixel 1,4,7 Track Block Sum	Derived	Derived	PEP/CAS					
297	Target Pixel 2,5,8 Track Block Sum	Derived	Derived	PEP/CAS					
298	TargetPixel 3,6,9 Track Block Sum	Derived	Derived	PEP/CAS					
299	Target Pixel 4,5,6 Track Block Sum	Derived	Derived	PEP/CAS					
300	Target Pixel 7,8,9 Track Block Sum	Derived	Derived	PEP/CAS					
301	Target Pixel Total Track Block Sum	Derived	Derived	PEP/CAS					
302	Telescope 1	2000	16	Target Board	32000			32000	
303	Telescope 2	2000	16	Target	32000			32000	

ID	Serial/Digital Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
				Board					
304	Telescope 3	2000	16	Target Board	32000			32000	
305	Telescope 4	2000	16	Target Board	32000			32000	
306	Telescope 5	2000	16	Target Board	32000			32000	
307	Telescope 6	2000	16	Target Board	32000			32000	
308	Telescope 7	2000	16	Target Board	32000			32000	
309	Telescope 8	2000	16	Target Board	32000			32000	
310	Telescope 9	2000	16	Target Board	32000			32000	
311	Telescope 10	2000	16	Target Board	32000			32000	
312	Telescope 11	2000	16	Target Board	32000			32000	
313	Telescope 12	2000	16	Target Board	32000			32000	
314	Telescope 13	2000	16	Target Board	32000			32000	
315	Telescope 14	2000	16	Target Board	32000			32000	
316	Telescope 15	2000	16	Target Board	32000			32000	
317	Telescope 16	2000	16	Target Board	32000			32000	
318	Telescope 17	2000	16	Target Board	32000			32000	
319	Telescope 18	2000	16	Target Board	32000			32000	
320	Telescope 19	2000	16	Target Board	32000			32000	
321	Telescope 20	2000	16	Target Board	32000			32000	
322	Telescope 21	2000	16	Target Board	32000			32000	
323	Telescope 22	2000	16	Target Board	32000			32000	
324	Telescope 23	2000	16	Target Board	32000			32000	
325	Telescope 24	2000	16	Target Board	32000			32000	
326	Telescope 25	2000	16	Target	32000			32000	

ID	Serial/Digital Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
				Board					
327	Telescope 26	2000	16	Target Board	32000			32000	
328	Telescope 27	2000	16	Target Board	32000			32000	
329	Telescope 28	2000	16	Target Board	32000			32000	
330	Telescope 29	2000	16	Target Board	32000			32000	
331	Telescope 30	2000	16	Target Board	32000			32000	
332	Telescope 31	2000	16	Target Board	32000			32000	
333	Telescope 32	2000	16	Target Board	32000			32000	
334	Telescope 33	2000	16	Target Board	32000			32000	
335	Telescope 34	2000	16	Target Board	32000			32000	
336	Telescope 35	2000	16	Target Board	32000			32000	
337	Telescope 36	2000	16	Target Board	32000			32000	
338	Telescope 37	2000	16	Target Board	32000			32000	
339	Telescope 1 - 40Hz	125	16	Target Board	2000			2000	
340	Telescope 2 - 40Hz	125	16	Target Board	2000			2000	
341	Telescope 3 - 40Hz	125	16	Target Board	2000			2000	
342	Telescope 4 - 40Hz	125	16	Target Board	2000			2000	
343	Telescope 5 - 40Hz	125	16	Target Board	2000			2000	
344	Telescope 6 - 40Hz	125	16	Target Board	2000			2000	
345	Telescope 7 - 40Hz	125	16	Target Board	2000			2000	
346	Telescope 8 - 40Hz	125	16	Target Board	2000			2000	
347	Telescope 9 - 40Hz	125	16	Target Board	2000			2000	
348	Telescope 10 - 40Hz	125	16	Target Board	2000			2000	
349	Telescope 11 - 40Hz	125	16	Target	2000			2000	

ID	Serial/Digital Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
				Board					
350	Telescope 12 - 40Hz	125	16	Target Board	2000			2000	
351	Telescope 13 - 40Hz	125	16	Target Board	2000			2000	
352	Telescope 14 - 40Hz	125	16	Target Board	2000			2000	
353	Telescope 15 - 40Hz	125	16	Target Board	2000			2000	
354	Telescope 16 - 40Hz	125	16	Target Board	2000			2000	
355	Telescope 17 - 40Hz	125	16	Target Board	2000			2000	
356	Telescope 18 - 40Hz	125	16	Target Board	2000			2000	
357	Telescope 19 - 40Hz	125	16	Target Board	2000			2000	
358	Telescope 20 - 40Hz	125	16	Target Board	2000			2000	
359	Telescope 21 - 40Hz	125	16	Target Board	2000			2000	
360	Telescope 22 - 40Hz	125	16	Target Board	2000			2000	
361	Telescope 23 - 40Hz	125	16	Target Board	2000			2000	
362	Telescope 24 - 40Hz	125	16	Target Board	2000			2000	
363	Telescope 25 - 40Hz	125	16	Target Board	2000			2000	
364	Telescope 26 - 40Hz	125	16	Target Board	2000			2000	
365	Telescope 27 - 40Hz	125	16	Target Board	2000			2000	
366	Telescope 28 - 40Hz	125	16	Target Board	2000			2000	
367	Telescope 29 - 40Hz	125	16	Target Board	2000			2000	
368	Telescope 30 - 40Hz	125	16	Target Board	2000			2000	
369	Telescope 31 - 40Hz	125	16	Target Board	2000			2000	
370	Telescope 32 - 40Hz	125	16	Target Board	2000			2000	
371	Telescope 33 - 40Hz	125	16	Target Board	2000			2000	
372	Telescope 34 - 40Hz	125	16	Target	2000			2000	

ID	Serial/Digital Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
				Board					
373	Telescope 35 - 40Hz	125	16	Target Board	2000			2000	
374	Telescope 36 - 40Hz	125	16	Target Board	2000			2000	
375	Telescope 37 - 40Hz	125	16	Target Board	2000			2000	
376	Telescope 2 Temperature	125	16	Target Board	2000			2000	
377	Telescope 36 Temperature	125	16	Target Board	2000			2000	
378	Telescope +5V -1	125	16	Target Board	2000			2000	
379	Telescope +15V -1	125	16	Target Board	2000			2000	
380	Telescope -15V -1	125	16	Target Board	2000			2000	
381	Telescope +5V -2	125	16	Target Board	2000			2000	
382	Telescope +15V -2	125	16	Target Board	2000			2000	
383	Telescope -15V -2	125	16	Target Board	2000			2000	
384	Power Supply 1 Temperature	125	16	Target Board	2000			2000	
385	Power Supply 2 Temperature	125	16	Target Board	2000			2000	
386	Sun Sensor	125	16	Target Board	2000			2000	
387	Relay Beam X Position	2000	16	Data Acq Sys	32000	32000		32000	
388	Relay Beam Y Position	2000	16	Data Acq Sys	32000	32000		32000	
389	Beacon Beam X Position	2000	16	Data Acq Sys	32000	32000		32000	
390	Beacon Beam Y Position	2000	16	Data Acq Sys	32000	32000		32000	
391	Beacon Beam Power	2000	16	Data Acq Sys	32000	32000		32000	
392	Relay Beam Power	2000	16	Data Acq Sys	32000	32000		32000	
393	Beacon Beam Coolant Temperature	125	16	Data Acq Sys	2000			2000	
394	Relay Beam Coolant Temperature	125	16	Data Acq Sys	2000			2000	
395	Laser Enclosure	125	16	Data	2000			2000	

ID	Serial/Digital Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
	Temperature			Acq Sys					
396	Ground	125	16	Data Acq Sys	2000			2000	
397	DAS +5V	125	16	Data Acq Sys	2000			2000	
398	DAS -5V	125	16	Data Acq Sys	2000			2000	
399	DAS -15V	125	16	Data Acq Sys	2000			2000	
400	Relay Beam Expander Adjustment	125	9	Data Acq Sys	1125			1125	
401	Beacon Beam Expander Adjustment	125	9	Data Acq Sys	1125			1125	
402	Relay Beam Chopping	2000	12	Data Acq Sys	24000			24000	
403	System Shutter Status	125	2	Data Acq Sys	250			250	
404	ATAS Shutter Status	125	1	Data Acq Sys	125			125	
405	Beacon Shutter Status	125	1	Data Acq Sys	125			125	
406	Relay Shutter Status	125	1	Data Acq Sys	125			125	
407	Sun Sense Status	125	1	Data Acq Sys	125			125	
408	Laser Modulator Period	2000	8	PAM/FSM	16000	16000		16000	
409	Residual Pointing Error - X	2000	16	PAM/FSM	32000	32000		32000	
410	Residual Pointing Error - Y	2000	16	PAM/FSM	32000	32000		32000	
411	XMT FSM Position -X	2000	16	PAM/FSM	32000	32000		32000	
412	XMT FSM Position -Y	2000	16	PAM/FSM	32000	32000		32000	
413	XMT FSM Position -X (3Hz)	125	16	PAM/FSM	2000	2000		2000	
414	XMT FSM Position -Y (3Hz)	125	16	PAM/FSM	2000	2000		2000	
415	XMT FSM Quad Sensor Intensity	500	16	PAM/FSM	8000	8000		8000	
416	XMT FSM Quad Sensor Intensity	500	16	PAM/FSM	8000	8000		8000	
417	RCV FSM Position -X	2000	16	PAM/FSM	32000	32000		32000	
418	RCV FSM Position -Y	2000	16	PAM/F	32000	32000		32000	

ID	Serial/Digital Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
				SM					
419	RCV FSM Position -X (3Hz)	125	16	PAM/FSM	2000	2000		2000	
420	RCV FSM Position -Y (3Hz)	125	16	PAM/FSM	2000	2000		2000	
421	RCV FSM Quad Sensor Intensity	500	16	PAM/FSM	8000	8000		8000	
422	RCV FSM Quad Sensor Intensity	500	16	PAM/FSM	8000	8000		8000	
423	PAM Sensor Intensity	500	16	PAM/FSM	8000	8000		8000	
424	PAM Sensor Intensity	500	16	PAM/FSM	8000	8000		8000	
425	PAM Position - X	500	16	PAM/FSM	8000	8000		8000	
426	PAM Position - Y	500	16	PAM/FSM	8000	8000		8000	
427	ADC Temperature	125	16	PAM/FSM	2000	2000		2000	
428	Driver Temperature	125	16	PAM/FSM	2000	2000		2000	
429	+5V Power Supply Current	125	16	PAM/FSM	2000	2000		2000	
430	+15V Power Supply Current	125	16	PAM/FSM	2000	2000		2000	
431	-15V Power Supply Current	125	16	PAM/FSM	2000	2000		2000	
432	FSM Drive Current	125	16	PAM/FSM	2000	2000		2000	
433	PAM Drive Current	125	16	PAM/FSM	2000	2000		2000	
434	+5V Power Supply Voltage	125	16	PAM/FSM	2000	2000		2000	
435	+15V Power Supply Voltage	125	16	PAM/FSM	2000	2000		2000	
436	-15V Power Supply Voltage	125	16	PAM/FSM	2000	2000		2000	
437	Drive Pwer Supply Voltage (+)	125	16	PAM/FSM	2000	2000		2000	
438	Drive Power Supply Voltage (-)	125	16	PAM/FSM	2000	2000		2000	
439	Reference Voltage	125	16	PAM/FSM	2000	2000		2000	
440	PAM Mode	125	2	PAM/FSM	250	250		250	
441	PAM Scan Status	125	1	PAM/F	125	125		125	

ID	Serial/Digital Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
				SM					
442	PAM Auto Scan Status	125	1	PAM/FSM	125	125		125	
443	PAM Dither Status	125	1	PAM/FSM	125	125		125	
444	PAM Intensity Level	125	1	PAM/FSM	125	125		125	
445	PAM Lead/Delay Mode	125	1	PAM/FSM	125	125		125	
446	PAM Mirror Lock	125	1	PAM/FSM	125	125		125	
447	XMT FSM Mode	125	1	PAM/FSM	125	125		125	
448	XMT FSM Quad Level	125	1	PAM/FSM	125	125		125	
449	XMT FSM Mirror Lock	125	1	PAM/FSM	125	125		125	
450	XMT FSM Range Gating Mode	125	1	PAM/FSM	125	125		125	
451	XMT FSM Command Mode	125	1	PAM/FSM	125	125		125	
452	RCV FSM Mode	125	1	PAM/FSM	125	125		125	
453	RCV FSM Quad Level	125	1	PAM/FSM	125	125		125	
454	RCV FSM Mirror Lock	125	1	PAM/FSM	125	125		125	
455	RCV FSM Range Gating Mode	125	1	PAM/FSM	125	125		125	
456	RCV FSM Command Mode	125	1	PAM/FSM	125	125		125	
457	PB-3 Time	125	48	MISC	6000				
458	Frame Counter	2000	4	MISC	8000				
459	TSS Data Flag	2000	1	MISC	2000				
460	TSS Calibration Data Flag	2000	1	MISC	2000				
461	TSS Snap Cal Data Flag	2000	1	MISC	2000				
462	TSS Snap Star Data Flag	2000	1	MISC	2000				
463	LSS Snap Star Data Flag	2000	1	MISC	2000				
464	LSS Snap Cal Data Flag	2000	1	MISC	2000				
465	LSS Calibration Data Flag	2000	1	MISC	2000				

ID	Serial/Digital Measurement	Sample Rate [Hz]	Bits Per Sample	Subsystem	Bit rate [Bps]	Format 1 (Payload & ACS)	Format 2 (Hlth)	Format 3 (Payload)	Format 4 (ACS & EPS)
466	LSS Data Flag	2000	1	MISC	2000				
467	Gimbal System Azimuth Position	125	20	MISC	2500				
468	Gimbal System Elevation Position	125	20	MISC	2500				
469	Hardware Hit Time	125	4	MISC	500				
470	Calculated Centroid X Correction	125	12	MISC	1500				
471	Calculated Centroid Y Correction	125	12	MISC	1500				
472	Hardware Coarse Hit Flag	125	1	MISC	125				
473	Software Coarse Hit Flag	125	1	MISC	125				
474	Fine Hit Flag	125	1	MISC	125				
475	Centroid Error Validity Flag	125	1	MISC	125				
476	Telescope Hit Level	125	5	MISC	625				
477	Center Telescope Hit Flag	125	1	MISC	125				
478	Even Telescope Hit Flag	125	1	MISC	125				
479	Odd Telescope Hit Flag	125	1	MISC	125				
480	Spare	6.25	12	MISC	75				
481	Spare	6.25	12	MISC	75				
482	Spare	6.25	12	MISC	75				
483	Spare	6.25	12	MISC	75				
484	Spare	6.25	12	MISC	75				
	TOTAL BIT RATE [bps]					525175.00	7650.00	1.84E+06	3306.25

APPENDIX E. TELEMETRY LIST ACRONYMS

Appendix E Telemetry List Acronyms
RM - Relay Mirror
FSM - Fast Steering Mirror
OM - Offset Mirror
CAS - Coarse Acquisition Sensor
Payload - Payload Experiment Package
B - Bilevel
A - Analog
S/D - Serial Digital
CEA - CAS Electronics Assembly
PMT - Photo Multiplier Tube
DIT - Differential Impedance Transducer (senses mirror position)
PAM - Point Ahead Mirror
BD/T - Beam Direction / Tracker
CSM - Command Storage Memory
DSU - Data Storage Unit
DTU - Digital Telemetry Unit
CP1 - Control Processor 1
CP2 - Control Processor 2
ACS - Attitude Control Subsystem
TT&C - Telemtry Tracking and Commanding Subsystem
PCU - Power Control Unit
EPS - Electrical Power Subsystem
V/T - Voltage / Temperature
TCS - Thermal Control Subsystem
WAVE - Wideband Angular Vibration Experiment
SP - Sensor Package
EP - Encoder Package
PCM - Pulse Coded Modulation
FPS - Fine Pointing Sensor
NEB - Non Essential Bus
FIFO - First In First Out
DAU - Data Acquisition Unit
FPA - Focal Plane Array
DAC - Digital to Analog Converter
MUX - Multiplexer
ADC - Analog to Digital Converter

Appendix E Telemetry List Acronyms
TFPA - Target Focal Plane Array
SFPA - Source Focal Plane Array
MISC - Miscellaneous

APPENDIX F. NPS SPACECRAFT POWER UP/DOWN CHECKLIST

√	Step	Action	Description	Notes
	1	Set Battery A Enable switch to OFF.	Stop charging the battery with external power.	
	2	Set Trickle Charger Primary Power switch to OFF.	Secure the trickle charger.	
	3	Disconnect Cable 101-J7 from interface port J-7 located on the minus X longeron of the spacecraft body	Disconnects the trickle charger from the spacecraft.	
	4	Connect cable W76 to the J-7 interface port located on the minus X longeron of the spacecraft body	Connects the in-flight jumper cable to the spacecraft.	
	5	Set Power Console (P.C.)Primary Power Control Panel circuit breakers to ON	Closes circuit breakers to power the P.C. Equipment	
	6	Set P.C. Primary Power Control power switch to ON	Applies power to the P.C. Equipment	
	7	Set P.C. Utility Power Supply (HP6267B) line on switch to ON	Applies 28 volts DC to the power monitor panel devices	
	8	Set P.C. Load Array Power Supply (HP6475C) line on switches to ON	Applies power to Load Arrays for batteries A, B, and C	
	9	Set P.C. Charge Array Power Supplies (HP6443B) line on switches to ON (3 switches)	Applies power to Charge Arrays for batteries A, B, and C	
	10	Set Digitial Voltmeter Model 5900 to the following configuration:	Places the digital voltmeter (dvm) in the power up configuration	
	10a	Power – ON		
	10b	Select – DCV		
	10c	Range to – AUTO		
	10d	Data output button – OUT		
	10e	Program control button – OUT		
	10f	Ratio button – OUT		
	10g	Filter button – OUT		

√	Step	Action	Description	Notes
	10h	Ext/rate dial – ANY POSITION		
	11	Set P.C. Power Monitor Panel to the following configuration:	Places the Power Monitor Panel in the power up configuration	
	11a	Power – ON		
	11b	Meter Range Select Battery Voltage A, B, C - '25- 35' Volts		
	11c	K1 Relay status A,B,C, D – CHARGE		
	11d	Battery A, B, C enable – OFF		
	11e	DVM select – Main bus voltage		
	12	Set P.C. Power Control Panel to the following configuration:	Places the Power Control Panel in the power up configuration	
	12a	Power – ON		
	12b	Meter range select A, B, C voltage – '30 –40' Volts		
	12c	Meter Range Select Main bus voltage – '25-45' Volts		
	12d	Battery control A, B, C bus enable– OFF (3 switches)		
	12e	Battery control A, B, C tap enable – OFF (3 switches)		
	12f	Battery control A, B, C charge enable- OFF (3 switches)		
	12g	Charge array power supply A, B, C circuit breakers – OFF (3 switches)		
	12h	Load array power supply circuit breakers – OFF (1 switch)		
	12I	DVM select – Main Bus Volt		
	12j	Ganged current limit – ON		
	12k	Voltage control – TURN DIAL FULLY CCW (zero volts on dvm)		
	12l	External mode/solar array simulator – SOLAR SIM		
	12m	Main bus enable – ON		

√	Step	Action	Description	Notes
	13	Connect Commanding line (AMFSK1/NCEU to AFSK/FLTSAT) and Telemetry line (J1 Data In/DSI 7103 to NRZL/FLTSAT) to Spacecraft at plus X longeron.	Connect commanding line to transmitter and telemetry line to receiver.	
	14	Adjust main bus to 36 ±2 volts using voltage control knob	Turn dial CW until the digital voltmeter measures 36 volts	
	15	Hold Filter Conditioning switch ON and enable battery A bus and tap	While the filter conditioning switch is in the up position, press the 'A bus enable' button to ON, then press the 'A tap enable' button to ON. Then release the filter conditioning switch.	
	16	Verify Frame synch on DSI 7103		
	17	GOTO ISCS SOFTWARE POWER UP/DOWN CHECKLIST AND CONDUCT COMMANDING OPERATION		
	18	FLTSAT EMERGENCY SHUTDOWN PROCEDURE		
	19	On Power Control Panel swtich DVM monitor to 'Battery A Voltage'.		
	20	Note Battery A voltage on DVM 5900		
	21	On Power Control Panel switch DVM Monitor to 'Main Bus Voltage'		
	22	Adjust Voltage control on Power Control Panel to match main bus voltage to battery A voltage		
	23	Press Battery Control 'A Tap Enable' OFF (dark) on Power Control Panel		
	24	Press battery Control 'A Bus Enable' OFF (dark) on Power		

√	Step	Action	Description	Notes
		Control Panel		
	25	Adjust Voltage Control for 'Main Bus Voltage' to 0.0 volts (turn know CCW)		
	26	Press Power Control 'Main Bus Enable' OFF (dark) on Power Control Panel		
	27	Set P.C. Power Control Panel Power switch OFF (dark)		
	28	Disconnect commanding and telemetry cables from spacecraft plus X longeron		
	29	Set P.C. Power Monitor Panel Power switch OFF (dark)		
	30	Set P.C. Charge Array Power Supplies (HP6443B) line on switches (3) to OFF (dark)		
	31	Set P.C. Load Array Power Supply (HP6475C) line on switch to OFF (dark)		
	32	Set P.C. Utility Power Supply (HP5257B) line on switch OFF (dark)		
	33	Set P.C. Primary Power Control Panel circuit breakers to OFF		
	34	Disconnect cable W76 from the J-7 interface port located on the minus X longeron of the spacecraft body.		
	35	Connect cable 101-J7 to the interface port J-7 located on the minus X longeron of the spacecraft body		
	36	Set Trickle Charge Primary Power switch to ON		
	37	Reset Overtemp alarm		
	38	Set Battery A Enable switch to ON		

APPENDIX G. NPS ISCS POWER UP/DOWN CHECKLIST

√	Step	Action	Description	Notes
	Note	If ISCS hardware is already on, and a FLTSAT_OPS> prompt is visible on the VT terminals start a step 12.		
	1	Set VAX expansion box power to ON	Applies power to BX-300	
	2	Set Time Code Generator power to ON	Applies power to Time Code Generator 800	Set system time for current time
	3	Set Modem Power to ON	Applies power to the modem	
	4	Set DECrouter Power to ON	Applies power to DECrouter	
	5	Set NCEU Power to ON	Applies power to NCEU	
	6	Set VAX 4000-100 power to ON	Applies power to the VAX	Power switch on back
	7	Set Printer power to ON	Applies power to printer	
	8	Set VT Terminal Power to ON	Applies power to VT Terminal	
	9	Type 'boot' and hit return at the triple chevron prompt	Starts the system boot up and enables the operating system: VMS 7.1	
	10	**Logon to the ISCS OPS account**		
	10a	If the VT console is attached to the FLTSAT node, login as 'OPS'. Password is 'aeronautics'		
	10b	If connected to the DEC Server 700, ('LOCAL>' is visible), type 'C FLTSAT' and return. Now login as OPS and use the password	Attach to the FLTSAT node and logon to the OPS account.	
	11	**Enter Personal User name**		
	11a	Use NPSLAB(FLTSAT7) or DOGLAW(VMAPR00) as username(password)	Authenticate ISCS privileges	
	12	**Start ISCS software processes**		
	12a	Type '@go' and return Observe the Short Cut Key list appear before moving to step 13.	Should be at the 'FLTSAT_OPS>' prompt indicating a Comet Command Line (CCL)/initiates the COMET session	Typing SHO SYS at the CCL on another console will display these ISCS processes: INITAL,RLC_O

√	Step	Action	Description	Notes
				UT,ODEXEC,SAC_GO, IOEXEC,AFTER_AT
	13	**Display the Resource Allocation Table (RAT)**		
	13a	Hit the period key on the keypad or type 'CRT RAT' and return		
	13b	Observe the current satellite links and console assignments		
	14	**Establish a link**		
	note	For COMET screens: line 1-20: data line 21: message line line 22: perform file display line line 23: alert line line 24: command line		PF 2 Acknowledge Alert PF 3 Print Screen PF 4 Clear Alert period CRT RAT 5 on keypad clears command system error flag
	14a	Type 'perf link_7.per' and return	Executes a perform file that executes: LINK L=1, S=7, INPDEV=XAA0, CEU=1, CEUTYPE=NCEU and return	Receives incoming FLTSAT telemetry to the software
	14b	Observe the 'EXIT' of the perform file		EXIT should appear on line 22 when the perform file finishes
	15	**Acknowledge all alerts**		
	15a	Hit the PF2 key	Acknowledge each alert	Alarms come in the form of alerts and can be seen on line 23
	15b	Repeat 15a until all alerts are cleared		The total number of alerts remaining is on the far right on line 23 in an orange box
	16	**Start ISCS on a second console**		
	16a	Type '@go' and return and observe the Short Cut Key	Starts ISCS processes for a second console	On a second console

√	Step	Action	Description	Notes
		List before moving to step 16b.		
	16b	Hit the period key on the keypad	Displays the RAT	On a second console
	16c	Type 'ATT L=1' and return	Attach the console to link 1	Attaches console 2 to the incoming telemetry stream. The RAT should update showing console 2 attached to link 1
	16d	Type 'CRT TTC' and return	Creates the TT&C screen	Displays incoming telemetry associated with the TT&C subsystem
	note	Additional displays are: THERMB, AVCSD, CC12, CC22, EPDS,		
	17	**Initiate commanding on console 1**		
	17a	On console 1, type 'bgncmd L=1' and return	Attaches the console to the link, executes CRT FLTCMD, and executes a command test	
	17b	Observe the NCEU error	Since ISCS does not have a KIT 223 (crypto equip.), an error will occur	
	18	**Clear the NCEU error**		
	18a	hit return		
	18b	hit PF4 key	clear the alert	
	18c	hit PF2 key	Acknowledge the alert	
	18d	type 'cont' and return	Continues the perform file	
	18e	Observe the perform file EXIT		EXIT should appear on line 22
	19	**Execute the soft reset**		
	19a	Type 'reset' and return	Performs a command system reset due to the NCEU error	
	19b	Observe 'Command System Reset Occurred' in line 21	Wait for the reset to be carried out.	Also observe the NCEU beep, Also CEU may say no lock on the TTC console

√	Step	Action	Description	Notes
	19c	Hit the '5' key on the keypad	Clears the commanding system error flag	
	20	**Verify telemetry is updating**		
	20a	Verify SFID is incrementing		
	20b	Verify system time is updating		
	21	**If telemetry is not updating goto step 24.**		
	22	**Change command states**		
	22a	Type 'cmdst iny=clear' and return	tells the software to configure for clear commands (no encrpytion)	
	22b	Type the letter of the current command unit and return	This should be the 'A' command unit (CU on the FLTCMD screen)	
	23	**Send the S1078 and S0380 Commands**		
	23a	Type 'CMD N=S1078' and return	Selects the dummy command S1078	
	23b	Verify the command data in the Command Selection Window: S1078 Dummy Command (15-1252)	The message line should ask if you would like to transmit the command.	
	23c	Type 'Y' and return if the command data is correct else type 'N' and return and goto step 24		
	23d	Verify the Command unit data and address are correct from the telemetry screen: CU1A = 7 CU1U=15		
		CU1D=1252		
	23e	If 23d is not correct repeat step 23a through 23d		
	23f	Type 'CMD N=S0380' and return	Selects the dummy command S0380	
	23g	Verify the command data in the Command Selection Window: S0380 AKM Ord Safe (EIA1-0140)	The message line should ask if you would like to transmit the command.	
	23h	Type 'Y' and return if the		

√	Step	Action	Description	Notes
		command data is correct else type 'N' and return and goto step 24		
	23i	Verify the Command unit data and address are correct from the telemetry screen: CU1A=7 CU1U=16 CU1D=0140		
	24	**End Commanding Session on Console 1**		
	24a	Type 'endcmd' and return		
	25	**Detach console 2**		
	25a	On console 2 type 'detach' and return	Detaches console 2 from the link.	All telemetry fields should become asterisks
	25b	Type 'LO' and return	Logs the console off the COMET session	
	26	**Detach console 1**		
	26a	On console 1 type 'detach' and return	Detaches console 2 from the link.	All telemetry fields should become asterisks
	27	Hit the period key on the keypad	Brings up the RAT	
	28	**Unlink the telemetry stream**		
	28a	Type 'perf unlink_7.per' and return	Unlinks the telemetry stream for the last console.	
	29	**Stop all COMET processes**		
	29a	Type 'term' and return	Terminates ISCS software processes.	
	29b	Type 'SHO SYS' and return	Verify all ISCS processes are stopped.	
	29c	Type 'STP' and return	Stops all processes that did not stop with the term command.	
	30	GOTO spacecraft power down procedure Step 18: Emergency Shutdown Procedure. All ISCS software has been stopped. Leave the software terminals in this configuration.		

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APPENDIX H. MITHRA REQUIREMENTS SUMMARY

This document is presented to provide additional information regarding the Mithra spacecraft requirements. This bifocal relay satellite was designed by the NPS satellite design team in the Summer quarter of 2000 for the AA 4871 Satellite Design Course.

Items to Demonstrate

- Bifocal relay concept
- Dynamically couple light energy from the satellite receiver to the satellite transmitter
- Ground to ground connectivity
- Maintain a directed light beam onto a specific "spot" and/or cooperative mobile target

Specific Requirements

Orbit:	1000 km baseline, can move up or down; maximize dwell time 40° inclination Minimum of 90 seconds dwell time for successful engagement Standard controlled deboost requirement Be aware of propellant contamination on optical surfaces
Demonstration Sites: Secondary Sites:	Kirtland AFRL and White Sands NM Maui AFRL, Edwards AFB, China Lake USN
Cost/Reliability:	$475M (FY 00), includes launch and testing 3 year operational life for demonstrator – traceable to 10 years operational life for operational vehicle
Launch Vehicle:	Heavier medium class vehicle (Atlas / Delta / EELV)
Payload:	3 m spot beam (goal) 3 m spot within 10 m area of uncertainty (AOU) Receive aperture beacon for acquisition and tracking (AFRL will provide system info from 1990-91 RME) "Transmit Sensor" will provide appropriate error signal to ACS (AFRL will develop system)

	Bus design will not preclude maintaining apertures at 1 °C differential (AFRL will develop this system as part of payload)
ACS:	LOS jitter < 0.25 RMS diffraction spread Analysis of settle time to LOS jitter spec for multiple (two) engagements per pass Maintain pointing and control of a beam from a fixed transmitter site onto a fixed target for an entire orbital pass above 30° elevation.
TT&C:	Minimize on-board processing Data rates compatible with AFSCN operations
Structure:	Sized to applicable launch vehicle
EPS:	Duty cycle, consider a minimum of one engagement per day

NPS Design Team Questions

Note: Not all these questions require specific answers. In some cases the questions have come up as areas for consideration, and may be fleshed out by the engineers during the design process.

Desired from AFRL (By 25 July 2000)

√ Payload size (or main aperture size) vs mass information
√ Payload cost (or main aperture cost) vs size/mass information
√ Receiver aperture beacon subsystem technical specifications/design
RME documentation
√ Transmit aperture imaging/area tracking subsystem (mass power data) specifications
√ Preliminary payload design
√ TT&C telemetry items required to determine mission success
(Measures of Effectiveness)

√ What is/are your most fundamental requirement(s)?
(1) jitter (2) cost (3) spot size (4) altitude [coverage]

√ Is there a specific CEP for the pointing accuracy of the spot beam?
10 m

√ Is there a technology freeze date?
2003

√ Is there a minimum/maximum TT&C data rate concern for any of the terrestrial support sites (other than AFSCN sites)? i.e. Maui, Kirtland, White Sands, Edwards, China Lake

√ Is there a requirement for monolithic or deployable mirrors?
Monolithic

√ What is/are the specific ground laser wavelength(s)? Is there a range (min/max)?
Nominally 1.0 micrometer

√ Will there be a requirement for any orbit plane changes/repositioning of the demonstration satellite?
No

√ What units should the design conform to? (Metric/English)
Metric

√ What are the deorbit requirements? (controlled/uncontrolled)
Controlled

√ Do the coupling mirrors have the same thermal control issues (1 °C differential) as the main optical mirrors? Subsystem requirements to be handled by AFRL

√ Is closed loop control required for both the receive and transmit sides of the demonstration vehicle? Yes

√ What parts of the payload operation require on-board processing?
Additional processing will be provided by payload

√ Is there a specific requirement for ephemeris? i.e. ranging data, GPS, both or other?

√ Will alternate commanding/receive sites (beyond the AFSCN) impose additional restrictions on bandwidth and uplink/downlink frequencies?
Action to TT&C engineer

√ Are there any specific requirements to buffer telemetry while out of view of a ground site (AFSCN or MCC)?
TBD by TT&C Engineer

√ Are there any specific requirements to have a command database on-board the satellite for execution while out of view of a ground site (AFSCN or MCC)?
TBD by TT&C Engineer

√ Are testing costs to be included in the $475 M?
Yes

√ What level of testing is required for the demonstration vehicle hardware/subsystems?
TBD by Cost /Reliability/Test Engineer

√ Are there any requirements of the overall system reliability figure? On subsystem reliability figures?
95% over 3 year for bus & payload

√ Desire clarification on the requirement to provide traceability to a 10 year design life for an operational vehicle.

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